Individual traffic significantly contributes to climate change and environmental degradation. Therefore, innovation in sustainable mobility is gaining importance as it helps to reduce environmental pollution. However, effects of new ideas in mobility are difficult to estimate in advance and strongly depend on the individual traffic participants. The application of agent technology is particularly promising as it focuses on modelling heterogeneous individual preferences and behaviours. In this paper, we show how agent-based models are particularly suitable to address three pressing research topics in mobility: 1. Social dilemmas in resource utilisation; 2. Digital connectivity; and 3. New forms of mobility. We then explain how the features of several agent-based simulators are suitable for addressing these topics. We assess the capability of simulators to model individual travel behaviour, discussing implemented features and identifying gaps in functionality that we consider important.

Keywords Traffic Simulation · Multi-agent Systems · Simulation Software

1 Introduction

Over the last decades, transportation and personal mobility have repeatedly faced radical changes. Driven by technological innovation and changing societal demands, traffic and transportation have evolved into complex systems. For example, Intelligent Transportation Systems (ITS) use advanced information technology to improve traffic management. Central traffic control systems are deployed to provide real-time information on road closures, parking space availability, etc. in order to minimise avoidable problems in traffic. In many countries, ITS are already in use with the main objectives to increase general traffic safety and to make more efficient use of the existing infrastructure. Computer-based simulations can be used to plan and assess the effects of new policies in advance, and provide decision support for transport planners and authorities. State of the art research on traffic simulation has shown a growing interest in the application of multi-agent models. Multi-agent models are implementations of Decentralised Artificial Intelligence [1]. They are an established means for the construction of synthetic worlds which can be used to simulate and analyse interactions of complex systems [1]. [2] provide a description of common structures found in agent platforms that are designed for the simulation of traffic. Agents are closed computer systems that are situated in some environment, and that are capable of autonomous action in this environment in order to meet their designed objectives [3]. This autonomous and goal-driven behaviour of intelligent software agents makes agent models particularly suitable for the representation of individuals in road traffic. For example, travellers can be modelled as agents that interact and perceive information about their environment through sensors, allowing for implementation of decentralised knowledge and thus autonomous behaviour based on situational conditions. This approach to modelling individuals is a key distinction of multi-agent approaches from other types of simulation models e.g. cellular automata [4].
As ideas on traffic simulation date back to the 1970s [5,6] a variety of computer-based simulators has been developed. Due to the broad spectrum of traffic simulators that have emerged over the years, interdisciplinary end-users working on specific research questions are faced with the issue of finding an appropriate simulation environment. [7] describe the phenomenon that in many cases instead of exploiting the potential of already existing simulators, researchers have implemented their own research specific applications. This may be the result of not having sufficient overview on the set of available simulators and their features which requires a considerable amount of in-depth research. In this paper, we reflect on current research topics in mobility and provide examples of simulators with related case studies. The paper specifically addresses the group of researchers that are studying individuals and their reciprocal effects on traffic to help them get an impression of the broad range of simulators and their capabilities to model individual travel behaviour.

This paper is organised as follows: The next section provides an overview of the diversity of traffic simulators and presents scope and areas of application of simulation models included in our review. We give examples of simulators with related case studies for each area of application. Following this, a review of simulators with regard to their background, system architecture and modelling capabilities is given. The review is primarily based on publications and publicly available discussions of expert communities. After that, we reflect on current state of implementation for modelling of individuals and discuss missing functionality that can help to improve research into simulation of individuals and their behaviour. The paper ends with a discussion of future steps that can help close these gaps.

2 Perspectives of Comparison

A search performed in September 2021 across three common publication databases: Google Scholar, ACM Digital Library and IEEE Xplore; delivered an overview of available simulators. We searched for peer-reviewed papers by keywords (1. Traffic Simulation; 2. Agent-based Traffic Simulation; 3. Multi-agent traffic simulation) contained in the title, abstract, and the main body of the papers. The first 30 research papers from each database and each keyword were included in a backward search to identify simulators that are considered related work by the authors of the publications. Furthermore, we also looked at some of the previous review papers [8][9][10] as well as forum discussions[11] from the research community in order to complete the search. With regard to the selection of papers included in this study, we only considered papers written in English and removed duplicate and irrelevant papers. We only looked at road traffic and excluded papers that focused on maritime or air traffic. In the case that different papers relate to the same simulator included in a backward search to identify simulators that are considered related work by the authors of the publications. We only looked at road traffic and excluded papers that focused on maritime or air traffic. In the case that different papers relate to the same simulator.

1. **Macroscopic simulations** focus on traffic flow modelling based on high-level mathematical models. This type of simulation can be used for the analysis of wide-area systems in which no detailed modelling is required, e.g. the simulation of motorway traffic. Given the low level of detail, macroscopic simulations are relatively fast and require less computing power.

2. **Microscopic simulations** focus on modelling individual entities based on a high level of detail. Possible entities include travellers, vehicles, traffic lights, etc. This type of simulation is often used for the analysis of urban traffic. It is possible to analyse both macroscopic and microscopic aspects (e.g. traffic lights algorithm, multimodal traffic) of the system. Consequently, microscopic simulations may result in longer computing times.

3. **Mesoscopic simulations** are a mixture of macroscopic and microscopic simulation models. Traffic entities are modelled at a higher level of detail than macroscopic approaches, however, interaction and behaviour of the individuals appear to be less detailed.

4. **Nanoscopic simulations** are even more detailed than microscopic approaches. This type of simulation is applied in the field of autonomous driving, in which internal functions of the vehicles such as gear shifting or vehicle vision have to be examined.

Agent models can be positioned as microscopic simulations that can also be used for research purposes with a higher level of detail (mesoscopic and macroscopic). The level of detail determines which aspects of the transport system are covered. Such differences are also reflected in the data required for modelling. The use of real-world data should increase the realism and accuracy of simulations. However, researchers need to be aware about the purpose of their simulation and choose a simulation model that supports the required level of detail for dealing with their research objectives. Going into more detail than necessary can make a simulation model complex and also requires more input data. If we consider macroscopic, microscopic and nanoscopic simulations, they all have two fundamental elements within the problem scenario that must be defined by the input data:

---

1e.g. [https://www.researchgate.net/post/What-is-the-best-agent-based-traffic-simulation-tool](https://www.researchgate.net/post/What-is-the-best-agent-based-traffic-simulation-tool) - (access on 13/05/2020)
• **Demand**: The demand element defines the requirement for travel and thus the resulting traffic volume between locations. This can be modelled using either activity- or trip-based approaches. Depending on the selected modelling approach different input data are required. For example, activity-based approaches use information from census and behaviour surveys to generate daily activity schedules of individuals and thus creates the need to travel. In contrast, trip-based approaches make use of origin-destination (OD) matrices which require no information on the daily schedules of individuals and thus allows for more abstract representation of traffic. However, trip-based approaches can also consider different levels of detail. At a macroscopic level this may be modelled through distributions of vehicles moving between larger areas, e.g. the number of vehicles per hour moving between a group of towns. Such information may come from traffic surveys or census data (e.g. giving the number of daily commuters between two towns). As we consider microscopic simulation, it becomes necessary to differentiate between individual vehicles. Rather than moving between two towns, demand may be in the form of specific journeys from an address to another address for a specific reason (e.g. commuting or shopping). Within mesoscopic simulation we might simulate journeys from a general location to a specific address, for instance commuter journeys that begin from a town, but travel to a specific employers’ address. In order to simulate at the microscopic levels, we move from a high level OD matrix to a more detailed OD matrix, with entries for specific addresses. As we begin to specify demand through specific journeys use of travel diaries and census information allows us to learn the travel habits of individuals. Nanoscopic simulation often focus on a smaller geographical area, demand may be represented by those journeys that are completely within the simulation as well as those that either pass through the simulation or only start/end within the area. Demand is likely to be specified as individual journeys, once again best specified using census or travel diary data.

• **Infrastructure**: The infrastructure element comprises a representation of the road network. At a fundamental level, the road network comprises a graph of nodes and arcs that represent junctions and roads respectively. The amount of detail required at the macroscopic level is minimal possibly denoting that a route between two towns exists and its capacity/travelling time, possibly only taking into account trunk routes. When using simulations for which greater levels of detail are required (e.g. microscopic and nanoscopic) it becomes necessary to include lower capacity roads and intermediate junctions in the road graph. At the microscopic level, the graph will need to contain information such as lane capacities, and junction types. At this level the difference made by features such as traffic signals, turn restrictions or lane closures may radically affect the outcome of the simulation. OpenStreetMap (OSM) [12] can provide a detailed source of road network data that can be applied at most levels of simulation.

In addition, the selection of algorithms significantly influences the options and limitations of the underlying simulation models. In this work, a distinction is made between the following categories: **fully agent-based**, **featuring agent technology** and **not agent-based**. We consider a simulator **fully agent-based** when key concepts of the simulation (e.g. travellers, vehicles) are fully implemented as intelligent software agents. This leverages the individual perspective in the modelling that comes with capabilities for interaction as well as autonomous and goal-driven behaviour. Simulators that use agent technology to extend alternative approaches by agent capabilities for specific aspects of the simulation are referred to as simulators that **feature agent technology**. Depending on the research objective general purpose platforms such as NetLogo [13] provide basic agent functionalities that can be used implement lightweight experiments. In this paper, we focus on simulators that are designed for simulation of large-scale scenarios as these are most relevant to implement real-world case studies. Our literature search has produces the following list of simulators for each category of simulation models:

- **Fully Agent-Based**: MATSim [14], ITSUMO [15], MovSim [16], MASCAT [17], MATISSE [18], POLARIS [19], AgentPoliS [7], OPUS [20], MOSAIC [21], MARS [22], SimMobility [23], SITRAS [24], ArchiSim [25], SEMSim (CityMOS) [26], JTSS [27], MegaNet ++ XAXIS [28], S-D Sim [29], S-MAT [30], VCT [31], SIMTUR [32], MUST [33], CAMiCS [34], OpEMCSS [35], DEFACTO [36], MAGE [37], CityScape [38], BAE Systems [39], AIISP [40], SeSam [41], IMAGES [42], Mobiliti [43], CUPSS [44], KLMTS1.0 [45], CARLA [46], AgentStudio [47], ILUTE [48], SIMULACRA [49], TransWorld [50].

- **Featuring Agent-Technology**: ATSim [51], FastTrans [52].

- **Not Agent-Based**: TRANSIMS [53], SUMO [54], OpenTraffic [55], CONTRAM [57], PTV VISUM [58], GETRAM/AIMSUM [59], PARAMICS [60], MITSIM [61], FreeSim [62], TSIS/CORSIM [63], VATSIM [64], DRACULA [65], RENAISSANCE [66], SimTraffic [67], DynaMIT [68], DYNASMART [69], MITSIMLab [70], CUBE Voyager [71], PELOPS [72], TransModeler [73], Dynameq [74], CORFLO [75], PACSIM [76], SIMSCRIPT II.5. [77], CTSP [78], CityMob [79], VaneoMobiSim [80], FIVIS [81], THOREAU [82], GENIVI [83], SLX [84], SALT [85], SIM-ENG [86], KAIST [87], UMTSM [88], SES/MB [89], SISTM [90], INTERGRATION [91], MATDYMO [92], TRANSYT [93].
As our objective is to address modelling of individuals, there is a primary focus on the approaches of the first and the second category. [94] have identified trending subjects in mobility for which a considerable amount of research and investment is currently focused. Based on these subjects, we consider three areas of application (Social dilemmas in resource Utilisation, Digital Connectivity and New Forms of Mobility) for which we give examples of simulators that have been used to research issues related to this domain. We are aware that areas of applications are closely connected and therefore may be overlapping. Hence, simulators mentioned as an example do not have to be used exclusively for the mentioned area of application, but can be particularly helpful. The simulators are studied with regard to three key aspects. We present general information (background, programming language, license, etc.) that is relevant to the selection of simulators and give an overview of the system architecture, describing basic functionalities of sub-components. Furthermore, we discuss implemented features for modelling individuals with regard to their area of application.

Modelling of individuals and their travel-related behaviour depends on the simulated level of detail which is closely linked to the considered time perspective of the simulation. **Long-term** aspects for example refer to decisions about workplace and residency whereas **short-term** decisions involve movements on a micro scale such as spontaneous interactions, lane changing, or acceleration and braking. **Mid-term** behaviour are in between and consider pre-journey planning such as route choice or selection of travel modes. The mid-term perspective distinguishes two types of approaches to modelling travel demand. This can be trip-based or activity-based. In trip-based approaches travel demand is modelled using OD-matrices (origin-destination) that can be based on static values or probability distributions. Alternatively, trip-based approaches can also be modelled using LSP (location-specific probabilities) usually resulting in travellers moving in space with no route specification. Instead, locations are assigned a pair of probabilities for the number of travellers starting as well as stopping at the location. In contrast to this, activity-based demand modelling for example produces a set of activities (e.g. working in the office, going to the gym, going grocery shopping) for each traveller, thus creating the need to travel. In this case, OD-matrices are a consequence of generated activity schedules. Considering this, we review modelling capabilities of simulators with regard to these aspects.

### 3 Review

As described in the previous section, we focus our review on agent-based approaches as our objective is to address the issue of modelling individuals. We concentrate on three areas of application: 1. Social Dilemmas in Resource Utilisation; 2. Digital Connectivity; 3. New Forms of Mobility. Due to the number of available simulators it is not possible to review all of them within the scope of this paper. Therefore, for each application we will look at three examples of simulators that have been used to model issues related to this domain.

#### 3.1 Social Dilemmas in Resource Utilisation

This application domain considers the issues arising from transport infrastructure inherently being a shared resource used by many individuals, but not owned by any one of them. This means that use of transport infrastructure by one individual often creates negative externalities that affect other individuals, e.g. congestion and pollution [95]. Better public transport and shared mobility services are intended to relieve the traffic load on roads, while electrification of vehicles is seen as a means to reduce exhaust fumes and environmental pollution. This creates new questions as to what effects will be achieved in the short term as well as in the long term. For example, E-mobility inevitably leads to a change in energy consumption that requires efficient planning of available resources. In this paper, we will look at MATSim, POLARIS and SimMobility as examples for agent-based simulators that have already been used to simulate issues in this context. Other simulators that also fall into this category include: SEMSim (CityMOS), Megaffic + X AXIS, MUST, CAMiCS, DEFACTO, CityScape, BAE Systems, SeSA m, Mobiliti, MARS, MOSAIIC, OPUS, ILUTE, SIMULACRA

##### 3.1.1 MATSim

MATSim is an agent-based software framework implemented in Java and licensed under GPLv2 or later. The project started in 2004 at ETH Zurich and is currently being developed in collaboration with TU Berlin and CNRS Lyon. The framework has a general focus and is designed for the simulation of large-scale transportation scenarios. Hence, a particular effort was made for efficient computational processing and parallelisation [96][97]. MATSim has been used in particular to simulate energy demand planning in transportation [98].

The framework consists of five components for **Initial Demand, Execution, Scoring, Replanning and Analysis** (see Figure 1). Based on the modular approach, custom components can be implemented and integrated into MATsim.
in order to replace or to upgrade provided default operations. The first component deals with modelling and generation of an initial agent population. Agents select and execute plans in the execution component. The scoring component calculates a score for every plan based on a given utility function. This score is an indicator for accomplished agent utility. The replanning component uses a co-evolutionary algorithm for optimising this utility. In contrast to an ordinary evolutionary algorithm that searches for a global optimum the co-evolutionary algorithm is applied to evolve the set of agent plans of the travellers. The simulation cycle (execution - scoring - replanning) repeats until MATSim reaches an equilibrium and agent scores stabilise. Finally, the output data of the simulation is being aggregated in the analysis component.

![MATSim - Architecture](image)

With regard to the modelling capabilities of the application, MATSim can be considered a mid-term simulator as scenarios are commonly modelled for single days [14]. However, there are some experiments that have demonstrated the simulation of multi-day scenarios [99]. MATSim provides two options for generating an initial population of agents which can be random or based on user input. Census information is used in order to model every traveller explicitly. The application provides a number of predefined parameters that can be configured. MATSim follows an activity-based approach for modelling travel demand. Survey data is used to generate various lists with activities that are assigned to the agents. It should be noted that travel demand changes with every iteration of the simulation as the simulation includes a replanning mechanism for rescheduling of activities. Furthermore, agents possess a list of plans that contains different combinations of actions and choices. This includes choices not only about classical traffic properties such as routes and travel mode but also time scheduling. MATSim uses a discrete-choice model for implementing agent decisions [14]. Quantitative methods are used to determine probabilistic distributions for alternative actions. Agents select plans based on calculated scores from the scoring component. A higher score increases the probability of a plan to be chosen (see [100]). Given the level of detail considered in modelling of individuals, MATSim is suitable for simulating scenarios that analyse social dilemmas in resource utilisation based on the amount and types of traffic (activities and modal choices) that emerges in the system.

### 3.1.2 POLARIS

POLARIS is an open-source agent-based software framework written in C++. The project was first published in 2013 (see [101]) and is currently maintained at Argonne National Laboratory. The motivation behind POLARIS was to combine different traffic-related modelling aspects into a single framework that otherwise require a number of separate standalone software applications. In [19], the authors of POLARIS argue that transportation research has focused on these aspects only in an isolated manner. However, simulation of complex systems requires a combined method. Early attempts to integrate the isolated models into a unified system have shown that resulting solutions are either inflexible, non-modular or inefficient. Based on this, the authors describe a need for a unified solution that enables inter-operability between the isolated models. The POLARIS framework has been proposed to address this issue [19]. POLARIS focuses on large-scale transportation scenarios and has been used to analyse energy consumption of vehicles in the city of Detroit comparing scenarios that include current and future vehicle technologies [102].

The framework provides a set of tools that can be used for the development, execution and review of a simulation model. The system architecture is structured using a layered approach (see Fig. 2). Aspect-specific subcomponents are assigned to a layer depending on the level of modelling detail. This ensures abstract concepts which are commonly used across different variations of traffic simulation models to be less likely to change. Instead, users are supposed to make research-specific customisations on a more detailed level. This creates reusability of frequently used modelling aspects. Based on this, layer 0 is the most abstract layer of the POLARIS framework. Layer 0 contains a set of core libraries such as the discrete event engine which is responsible for handling agents. Simulations are performed by executing a list of events. In layer 1, POLARIS contains a set of fundamental
extensions. This includes components for 2D/3D visualisation (Antares) or data import/export services. Layer 2 is described as an open-source versioned repository. In this repository, there is a set of model fragments that can be used for the implementation of custom simulation models. The provided model fragments are tested and chosen by universal applicability. Typical model fragments for example are reference implementations of well-established routing algorithms. Finally, layer 3 is described as the user playground. In this layer, custom components can be included in order to extend the POLARIS framework with research-specific modelling aspects. Based on the provided elements from all layers, the user can build a custom application for agent-based traffic simulation.

| Core Libraries                  | Final User Application |
|---------------------------------|------------------------|
| POLARIS Meta Structures         | Open-source Playground |
| Memory Allocator                | Experimental Transportation Algorithms |
| Discrete Event Engine           | Specialised Transportation Data Layouts |
| Interprocess Engine             |                       |
| Custom Data Containers          |                       |

Layer 0

Layer 1

Layer 2

Layer 3

Fundamental Extensions

Open-source Versioned Repository

Resusable Transportation Prototypes

Modular Transportation Algorithms

Fundamental Transportation Data Layouts

Experimental Transportation Algorithms

Specialised Transportation Data Layouts

Antares

Scenario Manager

Data Interchange Tools

Figure 2: POLARIS - Architecture.

With regard to modelling capabilities, POLARIS can be considered a mid-term simulator as travel decisions focus on mid-term aspects such as departure time, destination choice, route choices as well as planning and rescheduling of activities. Consequently, POLARIS uses an activity-based approach for modelling travel demand. This approach is based on an adjusted version of the ADAPTS (Agent-based Dynamic Activity Planning and Travel Scheduling) model [103]. Originally, the ADAPTS model has been designed as a standalone application for simulating the occurrence of travel demand patterns that result from travel planning and scheduling processes. For integration into the POLARIS framework, the ADAPTS model has been reorganised in order to match the agent paradigm. This resulted in a separate activity planning agent which as an extension to the traveller agent models the traveller’s cognition of the activity planning process. This illustrates the applied structure for modelling other types of behaviour in POLARIS as a central traveller agent is composed of a set of subagents which each extend the traveller agent with cognitive capabilities for specific behavioural aspects. For example, these include agents for perception, movement coordination or routing. In comparison to MATsim, this approach considers a more detailed modelling of individuals allowing for easier extension of short-term behaviour. This can be useful when energy consumption needs to be determined more precisely e.g. when simulating energy impact of acceleration and braking of autonomous vehicles to identify frequent nodes for charging stations.

3.1.3 SimMobility

SimMobility is a simulation platform written in C++ and published under an own open-source license. The project has related publications since 2015 and is currently developed at SMART (Singapore-MIT Alliance for Research and Technology) [104]. The simulator integrates a set of aspect-specific models relevant to the transportation domain that allows simulation on different time scales (short-, mid- and long-term) [23]. For example, aspect-specific models include land-use, demographic movement or interactions related to transportation and communication. The platform focuses on modelling effects on traffic infrastructure, transportation services and the environment. This allows for the simulation of alternative planning options specifically with regard to technology, policies and investment. SimMobility has been used to simulate the effects of new mobility services on the use of infrastructure [105].
The system architecture of SimMobility is structured in three components and follows a multi-level approach based on the time aspect. Each component simulates a different perspective (see Figure 3). The first component is the **Long-term (LT)** simulator. This component deals with generating and updating the agent population. The LT simulator particularly simulates long-term aspects such as house location and car ownership, but also other long-term effects such as changes to the environment can be simulated in this module. The second component is described as the **Mid-term (MT)** simulator. This component is primarily designed for the simulation of agent behaviour in time scales of minutes and hours. This refers to high level travel decisions such as route choice or modes of travel. The **Short-term (ST)** simulator is the last component in the multi-level architecture which is a microsimulator based on MITSIM that has been extended with agent capabilities. A special characteristic of this architecture is that each component can be used as a standalone application. All simulators share the same database so that simulated individuals exist across all simulation levels simultaneously.

![Figure 3: SimMobility - Architecture.](image)

With regard to the modelling capabilities, SimMobility covers all time perspectives (long-, mid- and short-term) considered in this review and therefore is particularly flexible and powerful. Modelling aspects are distributed across the three subcomponents but are brought together into an individual using one database. SimMobility follows an activity-based approach for modelling travel demand [23]. For each simulated day, the MT simulator generates a list of activities that include information on destination, departure time, route and mode choice. This approach has been integrated with methods of trip-based demand modelling as generated activities are aggregated to create origin-destination matrices that can be recalibrated. Agent decisions such as route choices are based on a probabilistic model which is similar to the MATSim approach [106]. The ST simulator also includes a mechanism that enables day-to-day agent learning to update the agent knowledge [23]. Based on these modelling capabilities, SimMobility is probably the most flexible and powerful approach in this area of application with regard to modelling of individuals. Researchers that are uncertain about the required level of detail in modelling individual behaviour are able to easily adapt using this application.

### 3.2 Digital Connectivity

The second type of application that we consider looks at the effect of the digital transformation on the mobility sector. For example, the use of digital traffic control systems (e.g. ITS), which can help to provide better driver experience for example by providing real-time information on parking and traffic jams, and also to improve transportation safety. In this paper, we look at the integration of SUMO and JADE as well as ITSUMO and MATISSE as examples of agent-based approaches that have been used for research on this type of simulation scenarios. Other simulators that also fall into this category include: SITRAS, ArchiSim, SM4T, SIMTUR, OpEMCSS, IMAGES, MASCAT, TransWorld

#### 3.2.1 An Integration of SUMO and JADE

**SUMO** (Simulation of Urban MOBility) is a software framework for microscopic traffic simulation written in C++ that is licensed under EPL 2.0. A first version of the project was published in 2001 and created by the German Aerospace Center (DLR) [53]. Since then, SUMO has been accepted by a wide community. The project was motivated by the necessity for an appropriate open-source solution as other projects which are now open-source, were difficult to obtain at that time [14]. Traffic applications were mainly used as black-boxes with no options to examine the underlying simulation model [54]. Thus, researchers were restricted by the given parameterisation and modelling with no options to implement custom ideas. The SUMO approach is not agent-based but has been integrated with the *Java Agent Development Framework (JADE)* (see [107]) in order to make simulations compatible with recent agent technologies [108, 109].
JADE is an open-source software framework licensed under LGPLv2 that is used for the implementation of agent-based applications. This combination of SUMO and JADE has been used for simulating and assessing the effects of traffic control systems [109][110]. The following section on the system architecture focuses on the integration of SUMO and JADE.

[108] have implemented a software connector that enables communication between the two software environments. This connector is referred to as TraSMAPI (Traffic Simulation Manager Application Programming Interface). From the SUMO perspective, the TraCI API is the central component for the integration of SUMO and JADE. TraSMAPI communicates with the TraCI API and acts as an intermediary. Although the project focuses on the integration of SUMO and JADE, TraSMAPI is abstracted to be able to handle various simulators besides SUMO (see Figure 4). This makes it possible to compare the results of different simulators. The combination of SUMO, JADE and TraSMAPI can therefore be termed as an Artificial Transportation System (ATS) which is an extension of traditional modelling and simulation approaches with the ability to integrate different simulation models in a virtual environment [111].

![Figure 4: TraSMAPI - Architecture.](image)

With regard to the modelling capabilities, this approach is suitable for mid- and short-term simulations as modelling aspects include selection of travel modes but also micro-behaviour such as lane changing. JADE agents represent drivers that are linked to vehicles in SUMO. A separation of strategic and tactic-reactive agent behaviour has been implemented with two layers which is also referred to as the delegate-agent concept [112]. Basically, it can be understood as a separation of cognitive and reactive actions from the executing driving tasks [108]. The strategic layer deals with collection and processing of information from the surrounding environment. Based on this information the agent chooses its travel route, also in the strategic layer. In the tactic-reactive layer driving related behaviour such as acceleration, braking or lane changing is implemented. Based on the functional requirements of the two layers, the strategic layer was kept in JADE whereas the tactic-reactive layer was realised in SUMO (see Figure 5). The original SUMO package provides two options for demand modelling which can be trip-based using an origin-destination matrix [11] or using an activity-based approach.

![Figure 5: Delegate-Agent Concept.](image)

Agent decisions are based on a probabilistic model but can be extended using the TraCI API. [108] have demonstrated the application of reinforcement learning techniques to model adaptable knowledge representation. Given the microscopic level of detail in modelling of individual behaviour, this application is suitable for simulating scenarios that analyse
effects of traffic control policies on driving behaviour of individuals e.g. examining the perception of digital and analog traffic signs.

### 3.2.2 ITSUMO

ITSUMO (Intelligent Transportation System for Urban Mobility) is an open-source agent-based traffic simulator written in C++ and Java. The simulator was first presented in 2006 by UFRGS (Federal University of Rio Grande do Sul) and since then has been continuously refined and advanced \[13, 15\]. Apart from the similarity in name, there is no direct link between ITSUMO and the previously described SUMO project. As the creators describe, ITSUMO was developed out of the lack of customising options in available simulation tools, as most of the existing solutions were developed for specific purposes. Other drawbacks described are for related simulation tools to not being fully agent-based, for them to be relying on strong simplifying assumptions, or deficiencies with regards to their demand planning options \[15\]. Thus, the ITSUMO approach is fully agent-based and aims at addressing the deficiencies mentioned above. ITSUMO has also been applied for the simulation of route choice scenarios. However, primary focus of the application is on traffic control. For example, ITSUMO has been used for testing traffic light algorithms \[114, 15\].

The system architecture is structured in five components \[115, 114\] (see Figure 6). The first component is a database. This database contains information about the geographic traffic network as well as other data used in the simulation (e.g. insertion rate of vehicles or origin and destination of the drivers). The second component is described as the simulation kernel. This component accesses data stored in the database, executes the simulation and manages agent interaction. The system architecture also includes a separate control component in which traffic-related control entities (e.g. traffic lights) are implemented. The control component passes information to the simulation kernel to provide instructions for simulated control entities. Finally, results of the simulation are output in a separate component. For this, sensors and detectors are used during the simulation in order to collect relevant data such as travel times, average speed, etc. The output module provides two visualisation options for both, a microscopic and macroscopic view of the simulation. If the visualisation is not used, simulation data can also be output as files.

![Figure 6: ITSUMO - Architecture.](image)

With regard to the modelling capabilities, ITSUMO can be considered a mid-term simulator that focuses on control and assignment of travel demand. Therefore, travel decisions refer to the level of route choice as well as its spontaneous replanning. Agents can either replan at every intersection or in case of a delay during the journey. ITSUMO follows a trip-based approach for modelling travel demand. Travel demand can be modelled using an origin-destination (OD) matrix or by generating a synthetic demand using uniform probabilities for a set of locations (LSP). For each combination of origin and destination, vehicles are generated and a route is determined. The application is particularly suitable for simulations that deal with ITS as it provides specific interfaces for implementing control measures and the driver reactions that are related to them.

### 3.2.3 MATISSE (DIVAs 4)

MATISSE is a large-scale agent-based simulation platform written in Java \[18, 116\]. The simulator has been released by UTD MAVS (University of Texas at Dallas) for non-commercial use under GPLv3 using name DIVAs 4. Early work related to the project has been published since 2004 during a time when only a few fully agent-based approaches existed \[117\]. Within this set of fully agent-based simulation models, the creators of MATISSE criticised the lack of core agent mechanisms such as sensing, diverse communication types, etc. The project has been developed to overcome these deficiencies. MATISSE specialises in the simulation of scenarios related to traffic safety.
The MATISSE architecture is structured in three layers (see Figure 7). The first layer is described as the **MATISSE Control and Visualisation Module**. It includes a control GUI for parameterisation and configuration of the simulation model. Furthermore, 2D/3D visualisation is implemented in this layer. Apart from this, there is a communication layer. This layer includes a **Message Transport Service** that acts as a controller in order to enable communication between the user interface and the simulation system. The third layer **MATISSE Simulation System** is the core element of the application. In this layer, calculations are performed in order to run the simulation. The layer is divided into three subsystems. The first subsystem is called **Agent System**. This subsystem is responsible for the creation and control of various agents types (vehicles, traffic lights, etc.). The **Agent-to-Agent Message Transport Service** handles agent communication during the simulation. The second subsystem is described as the **Environment System**. This subsystem creates and controls additional simulation elements related to the traffic environment. This includes elements such as the traffic network. A separate **Agent-Environment Message Transport Service** connects the environment system with the agent system. Finally, a third subsystem is the **Simulation Microkernel**. This subsystem handles all tasks related to the simulation workflow.

With regard to the modelling capabilities, MATISSE can be considered a mid- and short-term simulator as modelling aspects focus on driver behaviour. Similar to the ITSUMO approach, MATISSE also provides implementation for spontaneous replanning of route choices. Agent movement is based on car-following and lane-changing models, and it is even possible to model a virtual level of distraction that causes unpredicted traffic behaviour. The internal agent structure resembles a mental-level model from qualitative decision theory (see [118]) which can be useful for modelling individuals. Furthermore, mental-level models provide a uniform basis for the comparison of agent behaviour which helps theoretical analysis [119]. MATISSE follows a trip-based approach for modelling travel demand using LSP. MATISSE uses a normal distribution or a user specified distribution in order to initialise agents for defined user entry and exit points. The application is particularly suitable for dealing with simulations on transportation safety and already provides a wide range of implementations for this area of application. The implemented mental-level structure of agents in MATISSE can be helpful for researchers that want to expand in their work on modelling and analysis of individual travel behaviour.

### 3.3 New Forms of Mobility

Ideas on improving the use of shared resources as well as increasing connectivity driven by technological innovation leads to new forms of mobility, which we consider as our final application area. This includes the deployment of new mobility services (e.g. ridesharing or -hailing) but also achievements in the field of autonomous driving. Mobility thus is influenced by diverse interactions between travellers and providers of mobility services, but also (autonomous) vehicles. In this paper, we look at AgentPolis, ATSim and MovSim as examples of agent-based applications that can help to work on interactions with new mobility services or coordination dynamics of autonomous driving. Other simulators that also fall into this category include: SD-Sim, VCTS, AITSPS, CARLA
### 3.3.1 AgentPolis

AgentPolis is a fully agent-based software framework written in Java and licensed under GPLv3 [120][7]. The project was published in 2013 and created by AI Center FEE CTU (Czech Technical University in Prague). The creators noted that existing simulation approaches fail to implement the ability to model ad hoc interactions among the entities of the transport system as well as the spontaneous decision behaviour that is required for this form of interaction. However, current mobility services (e.g. ridesharing) rely on frequent, ad hoc interactions between various entities of the transport system. Hence, AgentPolis focuses particularly on the simulation of interaction-rich transport systems. For example, the simulator has been used as a testbed for benchmarking on-demand mobility services [121].

AgentPolis provides a set of abstractions, code libraries and software tools for building simulation models. The framework is structured in four main components (see Figure 8). The first component is described as the *modelling abstraction ontology*. The theoretical concept of this component is to separate defined modelling abstractions from implementations of specific modelling elements. It uses an ontology in order to define more general concepts of multi-agent systems that result in a tailored structure for object-oriented programming when extending the simulation models for research-specific scenarios. This allows for enforcement of implementations that consider interoperability of existing and additional research-specific modelling elements in their design. The second component is a *library of implemented modelling elements* based on the given abstractions specified in the ontology. The library contains a set of modelling elements that represent common entities in transport systems. Apart from this, the third component can be described as the *simulation engine*. This component performs all calculations for running the simulation based on a discrete event model. Finally, the last component is a set of tools for user interaction, particularly for configuration and creation of the simulation model, data import, visualisation, etc.

![AgentPolis Architecture](image)

With regard to the modelling capabilities, AgentPolis can be considered a mid-term simulator. Travel decisions refer to the level of route and modal choices. The agent structure is given by the abstraction ontology (see Figure 9) and defines concepts for the cognitive functions of the agent. Agents interact with objects in the environment using *sensors* and *activities*. Sensors perform queries to perceive environment objects while activities specify agent behaviour for initiating agent *actions*. Agent actions model the effects of the agent on its environment e.g. a *DriveVehicle* activity may result in a *MoveVehicle* action. [108] mention a clear separation in modelling of driver decisions and vehicle control and therefore implements decision-making of activities in a separate *reasoning module*. For this purpose, AgentPolis comes with implementation of a multimodal *JourneyPlanner* based on a time-dependent graph [122]. [120] have extended AgentPolis with custom reasoning modules implementing different routing algorithms that were relevant to their experiments. AgentPolis follows an activity-based approach for modelling travel demand. The simulator includes a tool that generates an initial population of agents based on census data [120]. Based on the level of decision-making and implemented features, AgentPolis has been used and is suitable for simulating demand and decisions on the adoption of new mobility services.
3.3.2 MovSim

MovSim (Multi-model open-source vehicular-traffic Simulator) is an agent-based traffic simulator written in Java and licensed under GPLv3. The project started in the late 1990s at TU Dresden and was designed for educational purposes [16]. In contrast to most available traffic simulation tools that model specific road networks (e.g. cities), MovSim focuses on the simulation of fundamental flow dynamics. For example, MovSim has been used to simulate the effects of driver movements on traffic jams, studying the appearance of stop-and-go waves [123]. Because of this particular focus on flow dynamics, MovSim has also been applied for the simulation of rather unconventional scenarios such as ski marathons [124]. The simulator includes a number of reference implementations for established mathematical car-following models as described in [125]. This can be relevant to simulate lane-changing and flow dynamics related to autonomous driving.

The MovSim architecture is structured in three layers (see Figure 10) [123]. In the input layer, simulation settings and parameters are defined. The user can input information either using a graphical user interface (GUI), command line or as XML files. This information is forwarded to the main loop layer. In this layer, agent control and movement are implemented. The simulation controller continuously calculates the simulation in a loop as MovSim is based on a time-continuous model. The simulation controller primarily focuses on quantitative models. Different submodules implement logic for aspect-specific agent behaviour such as acceleration, braking, lane-changing, etc. Two additional modules act as observers to the simulation loop in order to extract information for the output layer. The SimViewer module deals with information relevant for the visualisation of the simulated scenarios. MovSim includes implementation for both, 2D and 3D visualisation. Users can choose between a microscopic (cockpit perspective) or macroscopic (bird’s eye) view of the simulation. If the visualisation is not used, simulated data can also be output as files.

With regard to the modelling capabilities, MovSim can be considered a short-term simulator. Travel decisions refer to the level of agent movements such as acceleration, braking and lane changing. For this purpose, MovSim considers discrete-choice modelling. MovSim does not follow a trip- nor activity-based approach for demand modelling as route choices are irrelevant to the agent. Instead, agents represent particles in the network that move in space based on concepts of the applied car-following model. Hence, traffic volume can be defined using numerical input parameters [2]. Given the short-term perspective in modelling movement-related driver decisions, MovSim can be useful to simulate flow behaviour in the field of autonomous driving. The integration of MovSim as a submodule of a larger simulation environment specifically for short-term aspects can be of interest.

---

Footnote:

[123] MovSim (Multi-model open-source vehicular-traffic Simulator) is an agent-based traffic simulator written in Java and licensed under GPLv3. The project started in the late 1990s at TU Dresden and was designed for educational purposes [16]. In contrast to most available traffic simulation tools that model specific road networks (e.g. cities), MovSim focuses on the simulation of fundamental flow dynamics. For example, MovSim has been used to simulate the effects of driver movements on traffic jams, studying the appearance of stop-and-go waves [123]. Because of this particular focus on flow dynamics, MovSim has also been applied for the simulation of rather unconventional scenarios such as ski marathons [124]. The simulator includes a number of reference implementations for established mathematical car-following models as described in [125]. This can be relevant to simulate lane-changing and flow dynamics related to autonomous driving.

The MovSim architecture is structured in three layers (see Figure 10) [123]. In the input layer, simulation settings and parameters are defined. The user can input information either using a graphical user interface (GUI), command line or as XML files. This information is forwarded to the main loop layer. In this layer, agent control and movement are implemented. The simulation controller continuously calculates the simulation in a loop as MovSim is based on a time-continuous model. The simulation controller primarily focuses on quantitative models. Different submodules implement logic for aspect-specific agent behaviour such as acceleration, braking, lane-changing, etc. Two additional modules act as observers to the simulation loop in order to extract information for the output layer. The SimViewer module deals with information relevant for the visualisation of the simulated scenarios. MovSim includes implementation for both, 2D and 3D visualisation. Users can choose between a microscopic (cockpit perspective) or macroscopic (bird’s eye) view of the simulation. If the visualisation is not used, simulated data can also be output as files.

With regard to the modelling capabilities, MovSim can be considered a short-term simulator. Travel decisions refer to the level of agent movements such as acceleration, braking and lane changing. For this purpose, MovSim considers discrete-choice modelling. MovSim does not follow a trip- nor activity-based approach for demand modelling as route choices are irrelevant to the agent. Instead, agents represent particles in the network that move in space based on concepts of the applied car-following model. Hence, traffic volume can be defined using numerical input parameters [2]. Given the short-term perspective in modelling movement-related driver decisions, MovSim can be useful to simulate flow behaviour in the field of autonomous driving. The integration of MovSim as a submodule of a larger simulation environment specifically for short-term aspects can be of interest.

---

Footnote:

2. MovSim (Multi-model open-source vehicular-traffic Simulator) is an agent-based traffic simulator written in Java and licensed under GPLv3. The project started in the late 1990s at TU Dresden and was designed for educational purposes [16]. In contrast to most available traffic simulation tools that model specific road networks (e.g. cities), MovSim focuses on the simulation of fundamental flow dynamics. For example, MovSim has been used to simulate the effects of driver movements on traffic jams, studying the appearance of stop-and-go waves [123]. Because of this particular focus on flow dynamics, MovSim has also been applied for the simulation of rather unconventional scenarios such as ski marathons [124]. The simulator includes a number of reference implementations for established mathematical car-following models as described in [125]. This can be relevant to simulate lane-changing and flow dynamics related to autonomous driving.

The MovSim architecture is structured in three layers (see Figure 10) [123]. In the input layer, simulation settings and parameters are defined. The user can input information either using a graphical user interface (GUI), command line or as XML files. This information is forwarded to the main loop layer. In this layer, agent control and movement are implemented. The simulation controller continuously calculates the simulation in a loop as MovSim is based on a time-continuous model. The simulation controller primarily focuses on quantitative models. Different submodules implement logic for aspect-specific agent behaviour such as acceleration, braking, lane-changing, etc. Two additional modules act as observers to the simulation loop in order to extract information for the output layer. The SimViewer module deals with information relevant for the visualisation of the simulated scenarios. MovSim includes implementation for both, 2D and 3D visualisation. Users can choose between a microscopic (cockpit perspective) or macroscopic (bird’s eye) view of the simulation. If the visualisation is not used, simulated data can also be output as files.

With regard to the modelling capabilities, MovSim can be considered a short-term simulator. Travel decisions refer to the level of agent movements such as acceleration, braking and lane changing. For this purpose, MovSim considers discrete-choice modelling. MovSim does not follow a trip- nor activity-based approach for demand modelling as route choices are irrelevant to the agent. Instead, agents represent particles in the network that move in space based on concepts of the applied car-following model. Hence, traffic volume can be defined using numerical input parameters [2]. Given the short-term perspective in modelling movement-related driver decisions, MovSim can be useful to simulate flow behaviour in the field of autonomous driving. The integration of MovSim as a submodule of a larger simulation environment specifically for short-term aspects can be of interest.

2. MovSim (Multi-model open-source vehicular-traffic Simulator) is an agent-based traffic simulator written in Java and licensed under GPLv3. The project started in the late 1990s at TU Dresden and was designed for educational purposes [16]. In contrast to most available traffic simulation tools that model specific road networks (e.g. cities), MovSim focuses on the simulation of fundamental flow dynamics. For example, MovSim has been used to simulate the effects of driver movements on traffic jams, studying the appearance of stop-and-go waves [123]. Because of this particular focus on flow dynamics, MovSim has also been applied for the simulation of rather unconventional scenarios such as ski marathons [124]. The simulator includes a number of reference implementations for established mathematical car-following models as described in [125]. This can be relevant to simulate lane-changing and flow dynamics related to autonomous driving.

The MovSim architecture is structured in three layers (see Figure 10) [123]. In the input layer, simulation settings and parameters are defined. The user can input information either using a graphical user interface (GUI), command line or as XML files. This information is forwarded to the main loop layer. In this layer, agent control and movement are implemented. The simulation controller continuously calculates the simulation in a loop as MovSim is based on a time-continuous model. The simulation controller primarily focuses on quantitative models. Different submodules implement logic for aspect-specific agent behaviour such as acceleration, braking, lane-changing, etc. Two additional modules act as observers to the simulation loop in order to extract information for the output layer. The SimViewer module deals with information relevant for the visualisation of the simulated scenarios. MovSim includes implementation for both, 2D and 3D visualisation. Users can choose between a microscopic (cockpit perspective) or macroscopic (bird’s eye) view of the simulation. If the visualisation is not used, simulated data can also be output as files.

With regard to the modelling capabilities, MovSim can be considered a short-term simulator. Travel decisions refer to the level of agent movements such as acceleration, braking and lane changing. For this purpose, MovSim considers discrete-choice modelling. MovSim does not follow a trip- nor activity-based approach for demand modelling as route choices are irrelevant to the agent. Instead, agents represent particles in the network that move in space based on concepts of the applied car-following model. Hence, traffic volume can be defined using numerical input parameters [2]. Given the short-term perspective in modelling movement-related driver decisions, MovSim can be useful to simulate flow behaviour in the field of autonomous driving. The integration of MovSim as a submodule of a larger simulation environment specifically for short-term aspects can be of interest.

---

Footnote:

2. MovSim (Multi-model open-source vehicular-traffic Simulator) is an agent-based traffic simulator written in Java and licensed under GPLv3. The project started in the late 1990s at TU Dresden and was designed for educational purposes [16]. In contrast to most available traffic simulation tools that model specific road networks (e.g. cities), MovSim focuses on the simulation of fundamental flow dynamics. For example, MovSim has been used to simulate the effects of driver movements on traffic jams, studying the appearance of stop-and-go waves [123]. Because of this particular focus on flow dynamics, MovSim has also been applied for the simulation of rather unconventional scenarios such as ski marathons [124]. The simulator includes a number of reference implementations for established mathematical car-following models as described in [125]. This can be relevant to simulate lane-changing and flow dynamics related to autonomous driving.

The MovSim architecture is structured in three layers (see Figure 10) [123]. In the input layer, simulation settings and parameters are defined. The user can input information either using a graphical user interface (GUI), command line or as XML files. This information is forwarded to the main loop layer. In this layer, agent control and movement are implemented. The simulation controller continuously calculates the simulation in a loop as MovSim is based on a time-continuous model. The simulation controller primarily focuses on quantitative models. Different submodules implement logic for aspect-specific agent behaviour such as acceleration, braking, lane-changing, etc. Two additional modules act as observers to the simulation loop in order to extract information for the output layer. The SimViewer module deals with information relevant for the visualisation of the simulated scenarios. MovSim includes implementation for both, 2D and 3D visualisation. Users can choose between a microscopic (cockpit perspective) or macroscopic (bird’s eye) view of the simulation. If the visualisation is not used, simulated data can also be output as files.

With regard to the modelling capabilities, MovSim can be considered a short-term simulator. Travel decisions refer to the level of agent movements such as acceleration, braking and lane changing. For this purpose, MovSim considers discrete-choice modelling. MovSim does not follow a trip- nor activity-based approach for demand modelling as route choices are irrelevant to the agent. Instead, agents represent particles in the network that move in space based on concepts of the applied car-following model. Hence, traffic volume can be defined using numerical input parameters [2]. Given the short-term perspective in modelling movement-related driver decisions, MovSim can be useful to simulate flow behaviour in the field of autonomous driving. The integration of MovSim as a submodule of a larger simulation environment specifically for short-term aspects can be of interest.
3.3.3 ATSim

ATSim (Agent-based Traffic Simulation System) is an application based on the commercial simulator AIMSUN, that extends AIMSUN [59] with agent capabilities. The project was first published in 2011 and has been developed at TU Clausthal [51]. The authors of ATSim argue that for modelling the latest advances in transportation, an agent-based approach is crucial to represent important aspects of modern transportation such as communication, goals and plans. However, existing agent-based simulators have not focused on an intuitive graphical user interface and exhibit a lack of tools for data collection and data analysis. This is why in the ATSim approach, the commercial simulator AIMSUN has been integrated with the JADE platform [107]. This allows reuse of all features already implemented in AIMSUN while extending the simulator with agent capabilities. AIMSUN is used for modelling and simulation of traffic scenarios while implementation of agent behaviour is realised in JADE. ATSim has been used to simulate group-oriented traffic coordination in which groups of agents coordinate their speed and lane choices [126]. This can be relevant to simulate vehicle-to-vehicle (V2V) coordination dynamics related to autonomous driving.

The ATSim architecture is structured in four components (see Figure 11). The first component is the commercial AIMSUN simulator with all its features for modelling and simulating traffic scenarios. The second component is the multi-agent system based on JADE. This component is responsible for managing and controlling the agent life-cycle. In ATSim, agents are linked to various types of traffic objects in AIMSUN in order to extend AIMSUN objects with agent capabilities. Communication between agents and traffic objects is possible based on the AIMSUN API. AIMSUN provides an API for the integration of external services in Python and C++. However, JADE is based on Java and it is therefore necessary for ATSim to make use of a middleware in order to allow communication between AIMSUN and JADE.

With regard to modelling capabilities, ATSim can be considered a mid- and short-term simulator. Travel decisions refer to the level route choice but also agent movements based on established car following and lane changing models implemented in AIMSUN. These models have been extended by agent capabilities for modelling perception and interaction of individual travellers. A distinction is made between static objects, objects with dynamic states and mobile objects. For example, the road network is represented as a static object whereas traffic lights are modelled as objects with dynamic states and vehicles are presented as mobile objects. Traffic objects can be assigned to an agent in JADE. Each agent can only control a single object in AIMSUN. The link between the agents and traffic objects is based on two assumptions. First, the agent life-cycle is synchronised with the life-cycle of the associated traffic object. Second,
agents constantly receive updated information from the assigned traffic object after each simulation step. AIMSUM follows a trip-based approach for modelling travel demand using origin-destination matrices. The application has been used and thus is suitable for simulating V2V communication and coordination which is of growing relevance with the advancement of autonomous vehicles.

4 Discussion

Based on the simulators reviewed (see Table 1), it is apparent that modelling of individuals deals with differing aspects depending on the area of application. In our review we used the time perspective to categorise the simulators by their capabilities to model individual behaviour. For example, long- and mid-term aspects are more relevant for examining research on resource utilisation, while the simulation of autonomous driving (new forms of mobility) has a greater focus on short- and mid-term behaviour. For researchers that need to simulate aspects from all three time perspectives, for example when examining the effects of autonomous mobility services on individuals migrating to (sub-)urban areas (long-term), their modal choices (mid-term) and effects of such services on flow dynamics and traffic safety (short-term), Simmobility is appropriate as it can model all three time scales. Based on earlier case studies of the simulator we have mentioned SimMobility as an example for research on resource utilisation. However, examples do not have to be used exclusively in the described context. For researchers that need a holistic approach to modelling of individual behaviour, SimMobility can be a suitable candidate for shortlisting. Otherwise, the decision remains scenario-specific.

Table 1: A summary of reviewed simulators.

| Application Name | Area of Application | Licensing | Programming Language | Demand Modelling | Time Perspective on Individual Behaviour |
|------------------|---------------------|-----------|----------------------|-----------------|----------------------------------------|
| MATSim           | Resource Utilisation| GPLv2 or later | Java              | activity-based | mid-term                               |
| POLARIS          | Resource Utilisation| Open-source (license unclear) | C++              | activity-based | mid-term                               |
| SimMobility      | Resource Utilisation| SIMMOBILITY Version Control License (see Github) | C++              | activity-based | long-, mid- and short-term             |
| SUMO + JADE      | Connectivity        | LGPLv2 (SUMO) | C++, Java            | activity-based or trip-based using OD matrices | mid- and short-term |
| ITSUMO           | Connectivity        | Open-source (license unclear) | C++, Java | trip-based using OD matrices of LSP | mid-term |
| MATISSE (DIV As 4) | Connectivity      | GPLv3      | Java | trip-based using LSP | mid- and short-term |
| AgentPolis       | New Forms of Mobility | GPLv3 | Java | trip-based using OD matrices | mid-term |
| MovSim           | New Forms of Mobility | GPLv3 | Java | neither activity- nor trip-based. Only a numeric parameter to specify number of travellers. | short-term |
| ATSim            | New Forms of Mobility | Commercial | C++, Python, Java | trip-based using OD matrices | mid- and short-term |

With regard to the first application domain, which deals with social dilemmas in resource utilisation in the context of e-mobility, we consider SimMobility a more advanced approach in comparison to MATSim and POLARIS as it better handles the simulation of long-term aspects. This is particularly relevant to the simulation of urban areas as energy consumption is changing not only as a result of the electrification of vehicles, but also as a consequence of the increasing population caused by rural exodus. However, when dealing with mid-term scenarios MATSim and POLARIS can be just as powerful. In comparison to the other applications, MATSim probably has the largest user community and therefore is well documented whereas the POLARIS approach stands out in terms of the diversity of implemented features, as it combines various stand-alone applications into a single system.

Regarding the second application domain, digital connectivity benefits different aspects of the transportation system. When it comes to transportation safety, the MATISSE simulator is probably the most suitable application in this category as it specialises on this topic and provides dedicated features for modelling individuals in this context (e.g. driver distraction). However, for researchers that primarily want to test the effects of their custom algorithms in traffic management, ITSUMO can be more convenient as the application provides programming interfaces specifically for this purpose while already implementing a lot of details on individual behaviour (e.g. spontaneous or decentralised...
decision-making). The integration of SUMO and JADE can be relevant when used in the context of an ATS to compare different simulation models in a virtual environment.

The last application domain, new forms of mobility, is similarly diverse. When assessing the adoption of new mobility services, AgentPolis can be a good choice as the application focuses on the aspect of interaction when modelling individuals. This is particularly relevant as the growing portfolio of mobility services and continuous access to real-time information via smartphones have led to this dynamic. However, when dealing with research on autonomous driving modelling of individual behaviour focuses on movement related aspects. For this purpose, MovSim and ATSim can be of interest. MovSim in comparison to ATSim is a more lightweight simulator that exclusively deals with movement-related driving decisions from a theoretical perspective. ATSim can be used for the same type of decisions but is applied on real-world networks and includes mid-term decisions such as route choice.

The current state of implementation for modelling of individuals already shows a broad spectrum of features depending on area of application. Individual behaviour is modelled by traffic-related decisions at different levels of detail, e.g. lane changing vs. route or modal choices. However, we noticed that available simulators have focused on simulating traffic as the primary subject and thus leave scenario-specific aspects to the responsibility of end-users. Initially, a focus on traffic-related modelling aspects appears obvious as platform developers cannot anticipate the full range of scenarios for which their simulators will eventually be used. Following the same line of reasoning, developers need to assume that their applications will eventually be customised to fit specific research purposes. It is therefore desirable that common and foreseeable modifications are supported by suitable structures and programming interfaces. With regard to the modelling of individual behaviour, it is important to align traveller decisions with the context of the simulation. Traveller decisions are based on individual preferences and personal objectives. Furthermore, travel behaviour is typically driven by a purpose which plays a crucial role in the individual’s perception of personal preferences. For example, time/punctuality has a different value when commuting to work as compared to a social visit. However, in the current state of implementation there is a lack of concepts to capture these preferences and objectives as determining factors of individual decisions. This hampers customisation, especially for interdisciplinary researchers that are not thoroughly experienced with the simulators. Implementations that elaborate on modelling of these aspects can help reduce customisation efforts and thus attract more researchers to make use of available simulators rather than developing individual solutions as described by [7].

5 Conclusion

As diverse as the spectrum of research questions found in mobility, there is also a great variety of simulators that focus on different aspects of the transportation system and are differing in their underlying methods. Thus, getting an overview and selecting a suitable simulator can be time-consuming, involving a lot of in-depth research. The success of new ideas to solve current issues of transportation, such as sharing services or autonomous driving, relies on the acceptance and behaviour of individuals. Hence, it is important to focus on the individual when dealing with current research on mobility. For this purpose, computer-based simulations are an established means. The application of agent technology is particularly suitable to investigate road traffic from the individual perspective, as it allows for modelling of individuals with intelligent and autonomous behaviour. Current state of implementation includes a broad spectrum of features for modelling of individuals. Features are linked to the area of application, modelling individual behaviour at different levels of detail. Based on current research topics in the field of mobility, we have reviewed example simulators with related case studies and discussed the suitability of these simulators for specific research purposes. In particular, we have looked at the capabilities of the simulators to model individuals and their travel behaviour. Travel behaviour typically is linked to the context of the simulation and therefore needs to be adjusted. Currently, there is a lack of concepts to support this type of adjustments in the simulators, which hampers customisation especially for interdisciplinary researchers that are not thoroughly experienced with the simulators. Implementation for these types of adjustments can help to attract more researchers that deal with individual behaviour in mobility to make use of available simulators.

6 Acknowledgement

This research has been supported by a grant from the Karl-Vossloh-Stiftung (Project Number S0047/10053/2019).
References

[1] J. Ferber and G. Weiss. *Multi-agent systems: an introduction to distributed artificial intelligence*, volume 1. Addison-Wesley Reading, 1999.

[2] H. Zheng, Y.J. Son, Y.C. Chiu, L. Head, Y. Feng, H. Xi, S. Kim, M. Hickman, et al. A primer for agent-based simulation and modeling in transportation applications. Technical Report FHWA-HRT-13-054, United States. Federal Highway Administration, 2013.

[3] M. Wooldridge. Agent-based software engineering. *IEE Proceedings - Software Engineering*, 144(1):26, 1997.

[4] K.C. Clarke. Cellular automata and agent-based models. In *Handbook of Regional Science*, pages 1–16. Springer Berlin Heidelberg, 2018.

[5] M. Poeck and D. Zumkeller. Die anwendung einer massnahmenempfindlichen prognosemethode am beispiel des grossraums nürnberg. In *DVWG-Workshop Policy Sensitive Models, Giessen*, 1976.

[6] K.W. Axhausen and R. Herz. Simulating activity chains: German approach. *Journal of Transportation Engineering*, 115(3):316–325, may 1989.

[7] M. Jakob and Z. Moler. Modular framework for simulation modelling of interaction-rich transport systems. In *16th International IEEE Conference on Intelligent Transportation Systems (ITSC 2013)*, pages 2152–2159. IEEE, oct 2013.

[8] S. Algiers, E. Bernauer, M. Boero, L. Breheret, C. Di Taranto, M. Dougherty, K. Fox, and J.F. Gabard. Review of micro-simulation models. Last accessed 2021-09-27, 1997.

[9] M. Pursula. Simulation of traffic systems-an overview. *Journal of geographic information and decision analysis*, 3(1):1–8, 1999.

[10] L.S. Passos, R.J.F. Rossetti, and Z. Kokkinogenis. Towards the next-generation traffic simulation tools: a first appraisal. In *6th Iberian Conference on Information Systems and Technologies (CISTI 2011)*, pages 1–6. IEEE, 2011.

[11] P.A. Lopez, M. Behrisch, L. Bieker-Walz, J. Erdmann, Y. Flötteröd, R. Hilbrich, L. Lücken, J. Rummel, P. Wagner, and E. Wießner. Microscopic traffic simulation using SUMO. In *2018 21st International Conference on Intelligent Transportation Systems (ITSC)*, pages 2575–2582. IEEE, 2018.

[12] M. Haklay and P. Weber. OpenStreetMap: User-generated street maps. *IEEE Pervasive Computing*, 7(4):12–18, oct 2008.

[13] U. Wilensky et al. Netlogo. Center for connected learning and computer-based modeling, Northwestern University, 1999. Last accessed 2021-09-27.

[14] A. Horni, K. Nagel, and K.W. Axhausen. The Multi-Agent Transport Simulation MATSim. Ubiquity Press, aug 2016.

[15] A.L.C. Bazzan, M.d.B. do Amarante, T. Sommer, and A.J. Benavides. Itsumo: an agent-based simulator for its applications. In *Proc. of the 4th Workshop on Artificial Transportation Systems and Simulation*. IEEE, page 8, 2010.

[16] M. Treiber and A. Kesting. An open-source microscopic traffic simulator. *IEEE Intelligent Transportation Systems Magazine*, 2(3):6–13, 2010.

[17] M. Guériau, R. Billot, N.E. El Faouzi, J. Monteil, F. Armetta, and S. Hassas. How to assess the benefits of connected vehicles? a simulation framework for the design of cooperative traffic management strategies. *Transportation Research Part C: Emerging Technologies*, 67:266–279, jun 2016.

[18] B. Torabi, M. Al-Zinati, and R.Z. Wenkstern. MATISSE 3.0: A large-scale multi-agent simulation system for intelligent transportation systems. In *Advances in Practical Applications of Agents, Multi-Agent Systems, and Complexity: The PAAMS Collection*, pages 357–360. Springer International Publishing, 2018.

[19] J. Auld, M. Hope, H. Ley, V. Sokolov, B. Xu, and K. Zhang. POLARIS: Agent-based modeling framework development and implementation for integrated travel demand and network and operations simulations. *Transportation Research Part C: Emerging Technologies*, 64:101–116, mar 2016.

[20] Paul Waddell, Alan Borning, Hana Ševčíková, and David Socha. Opus (the open platform for urban simulation) and urbansim 4. In *Proceedings of the 2006 International Conference on Digital Government Research, dg.o ’06*, page 360–361. Digital Government Society of North America, 2006.

[21] G. Czura, P. Taillardand, P. Tranouez, and É. Daudé. Mosaic: City-level agent-based traffic simulation adapted to emergency situations. In *Proceedings of the International Conference on Social Modeling and Simulation, plus Éconophysics Colloquium 2014*, pages 265–274. Springer International Publishing, 2015.
[22] J. Weyl, D. Glake, and T. Clemen. Agent-based traffic simulation at city scale with mars. In *Proceedings of the Agent-Directed Simulation Symposium*, ADS ’18, San Diego, CA, USA, 2018. Society for Computer Simulation International.

[23] M. Adnan, F.C. Pereira, C.M.L. Azevedo, K. Basak, M. Lovric, S. Raveau, Y. Zhu, J. Ferreira, C. Zegras, and M. Ben-Akiva. Simmobility: A multi-scale integrated agent-based simulation platform. In *95th Annual Meeting of the Transportation Research Board Forthcoming in Transportation Research Record*, 2016.

[24] P Behbahanizadeh Hidas. Sitras: A simulation model for its applications. In *Towards the new together. Proceedings of the 5th World Congress on Intelligent Transport Systems*, number 3170, Seoul, Korea, 1998.

[25] Alexis Champion, Stéphane Éspié, and Jean-Michel Auberlet. Behavioral road traffic simulation with archisim. In *Summer Computer Simulation Conference*, pages 359–364. Society for Computer Simulation International; 1998, 2001.

[26] Yadong Xu, Heiko Aydt, and Michael Lees. SEMSim: A distributed architecture for multi-scale traffic simulation. In *Proceedings of the 26th Workshop on Principles of Advanced and Distributed Simulation*, pages 178–180. IEEE, IEEE, jul 2012.

[27] Cheng Tao and Shengguo Huang. An extensible multi-agent based traffic simulation system. In *2009 International Conference on Measuring Technology and Mechatronics Automation*, volume 3, pages 713–716. IEEE, IEEE, 2009.

[28] T Osogami, T Imamichi, H Mizuta, T Morimura, R Raymond, T Suzumura, R Takahashi, and T Ide. Ibm mega traffic simulator. Technical Report RT0896, IBM, 2012.

[29] Abdulai D. Dumbuya, R.L. Wood, T.J. Gordon, and Pete Thomas. An agent-based traffic simulation framework to model intelligent virtual driver behaviour, Jan 2002.

[30] Mahdi Zargayouna, Besma Zeddini, Gérard Scemama, and Amine Othman. Simulating the impact of future internet on multimodal mobility. In *2014 IEEE/ACS 11th International Conference on Computer Systems and Applications (AICCSA)*, pages 230–237. IEEE, IEEE, nov 2014.

[31] Gaurav Chaurasia, B Radhika Selvamani, Nithi Gupta, and Subodh Kumar. Virtual chaotic traffic simulation. In *Proceedings of the Seventh Indian Conference on Computer Vision, Graphics and Image Processing*, pages 337–344. ACM Press, 2010.

[32] Gilberto Nakamiti, Vinicius E. da Silva, José Henrique Ventura, and João Marcos A. Gonçalves. An agent-based simulation system for traffic control in the brazilian intelligent cities project context. In *Proceedings of the 2012 Symposium on Agent Directed Simulation*, ADS ’12, San Diego, CA, USA, 2012. Society for Computer Simulation International.

[33] Deepika Pathania, Bharath Vissapragada, Nahil Jain, Apeksha Khare, Soujanya Lanka, and Kamalakar Karlapalem. Must: Multi agent simulation of multi-modal urban traffic. In *Proceedings of the 2013 International Conference on Autonomous Agents and Multi-Agent Systems*, AAMAS ’13, page 1397–1398, Richland, SC, 2013. International Foundation for Autonomous Agents and Multiagent Systems.

[34] Jérôme Levesque, François Cazzolato, Jimmy Perron, Jimmy Hogan, Tony Garneau, and Bernard Moulin. Comics: Civilian activity modelling in constructive simulation. In *Proceedings of the 2008 Spring Simulation Multiconference*, SpringSim ’08, page 739–744, San Diego, CA, USA, 2008. Society for Computer Simulation International.

[35] John R Clymer. Simulation of a vehicle traffic control network using a fuzzy classifier system. In *Proceedings 35th Annual Simulation Symposium*. SS 2002, pages 285–291. IEEE, 2002.

[36] N. Schurr, J. Marecki, J.P. Lewis, M. Tambe, and P. Scerri. *The Defacto System: Coordinating Human-Agent Teams for the Future of Disaster Response*, pages 197–215. Springer US, Boston, MA, 2005.

[37] Arnaud Banos and Angèle Charpentier. Simulating pedestrian behavior in subway stations with agents. *Proceedings of the 4th European Social Simulation Association*, pages 611–621, 2007.

[38] Andreea Ion, Vlad Constantinescu, and Monica Patrascu. An agent based simulation model applied to emergency vehicles in high traffic urban environments. In *2015 Annual Global Online Conference on Information and Computer Technology (GOCICT)*, pages 104–108. IEEE, IEEE, nov 2015.

[39] David Handford, Alex Rogers, and Kevin Cross. Agent-based traffic operator training environments for evacuation scenarios. In *2011 IEEE/WIC/ACM International Conferences on Web Intelligence and Intelligent Agent Technology*, volume 2, pages 438–441. IEEE, IEEE, aug 2011.

[40] Li Zhou and Kai Zhao. The design of agent-based intelligent traffic visualized simulation system. In *2010 International Conference on Electrical and Control Engineering*, pages 3066–3069. IEEE, IEEE, jun 2010.
An Overview of Agent-Based Traffic Simulators - November 16, 2021

[41] Franziska Klügl, Rainer Herrler, and Manuel Fehler. Sesam: implementation of agent-based simulation using visual programming. In Proceedings of the fifth international joint conference on Autonomous agents and multiagent systems, pages 1439–1440. ACM Press, 2006.

[42] Jae-Bong Yoo, Ho-Min Jeong, BumJung Yoo, SangYoon Kim, and Chan Young Park. Images: intelligent multi-agent system for freeway traffic flow simulation. In 2009 International Conference on Information Networking, pages 1–5. IEEE, 2009.

[43] Cy Chan, Bin Wang, John Bachan, and Jane Macfarlane. Mobiliti: Scalable transportation simulation using high-performance parallel computing. In 2018 21st International Conference on Intelligent Transportation Systems (ITSC), pages 634–641. IEEE, nov 2018.

[44] Tingkai Wang, Shanyu Tang, and Peiyuan Pang. 3d urban traffic system simulation based on geo-data. In ITRE 2004. 2nd International Conference Information Technology: Research and Education, pages 59–63. IEEE, 2004.

[45] Feng Chen and Hao Pang. Study of multi-agent area coordination control for urban traffic. In 2008 7th World Congress on Intelligent Control and Automation, pages 4046–4050. IEEE, 2008.

[46] Alexey Dosovitskiy, German Ros, Felipe Codevilla, Antonio Lopez, and Vladlen Koltun. CARLA: An open urban driving simulator. In Sergey Levine, Vincent Vanhoucke, and Ken Goldberg, editors, Proceedings of the 1st Annual Conference on Robot Learning, volume 78 of Proceedings of Machine Learning Research, pages 1–16. PMLR, 13–15 Nov 2017.

[47] Michal Radecký and Petr Gajdoš. Intelligent agents for traffic simulation. In Proceedings of the 2008 Spring Simulation Multiconference, SpringSim ’08, page 109–115, San Diego, CA, USA, 2008. Society for Computer Simulation International.

[48] Paul Salvini and Eric J Miller. ILUTE: An operational prototype of a comprehensive microsimulation model of urban systems. Networks and Spatial Economics, 5(2):217–234, jun 2005.

[49] Michael Batty, Camilo Vargas, Duncan Smith, Joan Serras, Jon Reades, and Anders Johansson. SIMULACRA: Fast land-use—transportation models for the rapid assessment of urban futures. Environment and Planning B: Planning and Design, 40(6):987–1002, dec 2013.

[50] Fei-Yue Wang. Parallel control and management for intelligent transportation systems: Concepts, architectures, and applications. IEEE Transactions on Intelligent Transportation Systems, 11(3):630–638, sep 2010.

[51] V.H. Chu, J. Görmer, and J.P. Müller. Atsim: Combining aimsum and jade for agent-based traffic simulation. In Proceedings of the 14th Conference of the Spanish Association for Artificial Intelligence (CAEPIA), volume 1, 2011.

[52] S. Thulasidasan, S. Kasiviswanathan, S. Eidenbenz, E. Galli, S. Mniszewski, and P. Romero. Designing systems for large-scale, discrete-event simulations: Experiences with the fasttrans parallel microsimulator. In 2009 International Conference on High Performance Computing (HiPC), pages 428–437. IEEE, IEEE, dec 2009.

[53] Texas Transportation Institute. Early deployment of transims: Issue paper. Technical report, Federal Highway Administration Washington, DC, 1999.

[54] D. Krajzewicz, G. Hertkorn, C. Rössel, and P. Wagner. Sumo (simulation of urban mobility)-an open-source traffic simulation. In Proceedings of the 4th middle East Symposium on Simulation and Modelling (MESM2002), pages 183–187, 2002.

[55] M. Miska, E. Santos, E. Chung, and H. Prendinger. Opentraffic-an open source platform for traffic simulation. In Australasian Transport Research Forum, 2011.

[56] G. Tamminga, Peter K., and J.W.C. Van Lint. Open traffic: A toolbox for traffic research. Procedia Computer Science, 32:788–795, 2014.

[57] N.B. Taylor. The contrad dynamic traffic assignment model. Networks and spatial economics, 3(3):297–322, 2003.

[58] M. Fellendorf. Vissim: A microscopic simulation tool to evaluate actuated signal control including bus priority. In 64th Institute of Transportation Engineers Annual Meeting, volume 32, pages 1–9. Springer, 1994.

[59] Jaime Barceló and Jordi Casas. Dynamic Network Simulation with AIMSUN, pages 57–98. Springer US, Boston, MA, 2005.

[60] G.D.B. Cameron and G.I.D. Duncan. PARAMICS - parallel microscopic simulation of road traffic. The Journal of Supercomputing, 10(1):25–53, 1996.

[61] Q. Yang, H.N. Koutsopoulos, and M.E. Ben-Akiva. Simulation laboratory for evaluating dynamic traffic management systems. Transportation Research Record, 1710(1):122–130, jan 2000.
AN OVERVIEW OF AGENT-BASED TRAFFIC SIMULATORS - NOVEMBER 16, 2021

[62] J. Miller and E. Horowitz. FreeSim - a free real-time freeway traffic simulator. In 2007 IEEE Intelligent Transportation Systems Conference, pages 18–23. IEEE, IEEE, sep 2007.

[63] L.E. Owen, Y. Zhang, L. Rao, and G. McHale. Traffic flow simulation using corsim. In 2000 Winter Simulation Conference Proceedings, volume 2, pages 1143–1147. IEEE, 2000.

[64] J. Lei, K. Redmill, and U. Ozguner. Vatsim: A simulator for vehicles and traffic. In 2001 IEEE Intelligent Transportation Systems Proceedings, pages 686–691. IEEE, 2001.

[65] R. Liu. Traffic simulation with DRACULA. In Fundamentals of Traffic Simulation, pages 295–322. Springer New York, 2010.

[66] Y. Wang, M. Papageorgiou, and A. Messmer. RENAISSANCE – a unified macroscopic model-based approach to real-time freeway network traffic surveillance. Transportation Research Part C: Emerging Technologies, 14(3):190–212, jun 2006.

[67] D.K. Sorenson and J. Collins. Practical applications of traffic simulation using simtraffic. In Compendium of Papers. Institute of Transportation Engineers 2000, District 6 Annual Meeting, 2000.

[68] Moshe Ben-Akiva, Michel Bierlaire, Haris Koutsopoulos, and Rabi Mishalani. Dynamit: a simulation-based system for traffic prediction. In DACCORD short term forecasting workshop, pages 1–12. Delft The Netherlands, 1998.

[69] Hani S Mahmassani and Srinivas Peeta. Network performance under system optimal and user equilibrium dynamic assignments: implications for advanced traveler information systems. Transportation Research Record, 1408:83, 1993.

[70] Qi Yang and Haris N Koutsopoulos. A microscopic traffic simulator for evaluation of dynamic traffic management systems. Transportation Research Part C: Emerging Technologies, 4(3):113–129, jun 1996.

[71] Bentley Systems. Cube voyager: Predictive modeling and simulation of transportation, 2021. Last accessed 2021-09-24.

[72] H Wallentowitz, D Neunzig, and J Ludmann. Effects of new vehicle and traffic technologies — analysis of traffic flow, fuel consumption and emissions with PELOPS. In Traffic and Mobility, pages 181–191. Springer Berlin Heidelberg, 1999.

[73] Ramachandran Balakrishna, Daniel Morgan, Howard Slavin, and Qi Yang. Large-scale traffic simulation tools for planning and operations management. IFAC Proceedings Volumes, 42(15):117–122, 2009.

[74] Michael Mahut and Michael Florian. Traffic simulation with dynameq. In Fundamentals of Traffic Simulation, pages 323–361. Springer New York, 2010.

[75] H Lieu, AJ Santiago, and A Kanaan. Corflo. an integrated traffic simulation system for corridors. In Traffic Management. Proceedings of the Engineering Foundation ConferenceEngineering Foundation, 1992.

[76] Eric Cornelis and Ludovic Platbrood. Pacsim : a dynamic, behavioural and multimodal urban traffic simulation model. pages 81–85, 2002. Publication editors : Fernando J. baroos, Norbert Giambiasi.

[77] Willi Bernhard and Peter Portmann. Traffic simulation of roundabouts in switzerland. In 2000 Winter Simulation Conference Proceedings, volume 2, pages 1148–1153. IEEE, 2000.

[78] Atilla Elci and Ali Zambakoğlu. City traffic simulation package and its utilization. ACM SIGSIM Simulation Digest, 13(1-4):7–11, jan 1982.

[79] Francisco J Martinez, J-C Cano, Carlos T Calafate, and Pietro Manzoni. CityMob: A mobility model pattern generator for VANETs. In ICC Workshops - 2008 IEEE International Conference on Communications Workshops, pages 370–374. IEEE, IEEE, may 2008.

[80] Jérôme Härri, Fethi Filali, Christian Bonnet, and Marco Fiore. Vanetmobisim: generating realistic mobility patterns for vanets. In Proceedings of the 3rd international workshop on Vehicular ad hoc networks, pages 96–97. ACM Press, 2006.

[81] Oliver Schulzyk, Jens Bongartz, Tobias Bildhauer, Ulrich Hartmann, B Goebel, R Herpers, and Dietmar Reinert. A bicycle simulator based on a motion platform in a virtual reality environment—fivis project. In Advances in Medical Engineering, pages 323–328. Springer, 2007.

[82] Paul TR Wang and Richard A Glassco. Enhanced THOREAU traffic simulation for intelligent transportation systems (ITS). In Proceedings of the 27th conference on Winter simulation, pages 1110–1115. IEEE, ACM Press, 1995.
Bihao Wang, Marwa Mahmoud, Javier Echevarría Cuesta, Hannah Close, Quentin Stafford-Fraser, and Peter Robinson. Enhanced traffic simulation for improved realism in driving simulators. In *Adjunct Proceedings of the 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, pages 170–174. ACM, sep 2018.

James O Henriksen. Slx: the x is for extensibility [simulation software]. In *2000 Winter Simulation Conference Proceedings*, volume 1, pages 183–190. IEEE, 2000.

Hyewon Song and Okgiee Min. Statistical traffic generation methods for urban traffic simulation. In *2018 20th International Conference on Advanced Communication Technology (ICACT)*, pages 247–250. IEEE, IEEE, feb 2018.

J.M. Creagh. Sim-eng: a traffic simulation engine. In *Proceedings 32nd Annual Simulation Symposium*, pages 4–10. IEEE Comput. Soc, 1999.

Dong-Soo Kwon, Gi-Hun Yang, Chong-Won Lee, Jae-Cheol Shin, Youngjin Park, Byungbo Jung, Doo Yong Lee, Kyungno Lee, Soon-Hung Han, Byoung-Hyun Yoo, et al. Kaist interactive bicycle simulator. In *Proceedings 2001 ICRA. IEEE International Conference on Robotics and Automation*, volume 3, pages 2313–2318. IEEE, 2001.

Ben Zhang, Lei Shang, and Dan Chen. A study on the traffic intersection vehicle emission base on urban microscopic traffic simulation model. In *2009 First International Workshop on Education Technology and Computer Science*, volume 2, pages 789–794. IEEE, 2009.

Sung-Do Chi, Ja-Ok Lee, and Young-Kwang Kim. Discrete event modeling and simulation for traffic flow analysis. In *1995 IEEE International Conference on Systems, Man and Cybernetics. Intelligent Systems for the 21st Century*, volume 1, pages 783–788 vol.1. IEEE, 1995.

EJ Hardman. Motorway speed control strategies using SISTM. In *Eighth International Conference on Road Traffic Monitoring and Control*. IEE, 1996.

M Van Aerde, B Hellinga, M Baker, and H Rakha. Integration: An overview of traffic simulation features. *Transportation Research Records*, 1996.

KY CHOI, SJ Kwon, and MW Suh. Development of matdymo (multi-agent for traffic simulation with vehicle dynamics model) i: Development of traffic environment. *International Journal of Automotive Technology*, 7(1):25–34, 2006.

AS Byrne, KG Courage, and CE Wallace. Handbook of computer models for traffic operations analysis. Technical Report FHWA-TS-82-213, 1982.

T. Möller, A. Padhi, D. Pinner, and A. Tschiesner. The future of mobility is at our doorstep. *McKinsey Center for Future Mobility*, 2019. Last accessed 2021-09-24.

C. Dobler and K.W. Axhausen. Design and implementation of a parallel queue-based traffic flow simulation. *Arbeitsberichte Verkehrsw-und Raumplanung*, 732, 2011.

D. Charypar. *Efficient algorithms for the microsimulation of travel behavior in very large scenarios*. PhD thesis, ETH, Eidgenössische Technische Hochschule Zürich, 2008.

T. Novosel, L. Perković, M. Ban, H. Keko, T. Pukšec, G. Krajačić, and N. Duić. Agent based modelling and energy planning – utilization of MATSim for transport energy demand modelling. *Energy*, 92:466–475, dec 2015.

A. Horni and K.W. Axhausen. Matsim agent heterogeneity and a one-week scenario. *Arbeitsberichte Verkehrsw-und Raumplanung*, 836, 2012.

G. Flötteröd and B. Kickhöfer. Choice models in MATSim. In *The Multi-Agent Transport Simulation MATSim*, pages 337–346. Ubiquity Press, aug 2016.

J. Auld, M. Hope, H. Ley, B. Xu, K. Zhang, and V. Sokolov. Modelling framework for regional integrated simulation of transportation network and activity-based demand (polaris). In *Proceedings of the International Symposium for Next Generation Infrastructure*. University of Wollongong, SMART Infrastructure Facility, 2014.

E. Islam, A. Mouwad, J. Auld, D.A. Karbowski, and A. Rousseau. Impact of advanced vehicle technologies on energy consumption for the city of detroit using transportation system simulations. In *2017 IEEE Vehicle Power and Propulsion Conference (VPPC)*, pages 1–6. IEEE, dec 2017.

J. Auld and A. Mohammad. Framework for the development of the agent-based dynamic activity planning and travel scheduling (ADAPTS) model. *Transportation Letters*, 1(3):245–255, jul 2009.
[104] Y. Lu, M. Adnan, K. Basak, F.C. Pereira, C. Carrion, V.H. Saber, H. Loganathan, and M.E. Ben-Akiva. Simmobility mid-term simulator: A state of the art integrated agent based demand and supply model. In 94th Annual Meeting of the Transportation Research Board, Washington, DC, 2015.

[105] K.A. Marczuk, H.S.S. Hong, C.M.L. Azevedo, M. Adnan, S.D. Pendleton, E. Frazzoli, et al. Autonomous mobility on demand in SimMobility: Case study of the central business district in singapore. In 2015 IEEE 7th International Conference on Cybernetics and Intelligent Systems (CIS) and IEEE Conference on Robotics, Automation and Mechatronics (RAM), pages 167–172. IEEE, jul 2015.

[106] C.L. Azevedo, N.M. Deshmukh, B. Marimuthu, S. Oh, K. Marczuk, H. Soh, K. Basak, T. Toledo, L.S. Peh, and M.E. Ben-Akiva. SimMobility short-term: An integrated microscopic mobility simulator. Transportation Research Record: Journal of the Transportation Research Board, 2622(1):13–23, jan 2017.

[107] F. Bellifemine, F. Bergenti, G. Caire, and A. Poggi. Jade — a java agent development framework. In Multi-Agent Programming, pages 125–147. Springer US, 2005.

[108] G. Soares, Z. Kokkinogenis, J.L. Macedo, and R.J.F. Rossetti. Agent-based traffic simulation using SUMO and JADE: An integrated platform for artificial transportation systems. In Simulation of Urban Mobility, pages 44–61. Springer Berlin Heidelberg, 2014.

[109] T. Azevedo, P.J.M. De Araújo, R.J.F. Rossetti, and A.P.C. Rocha. Jade, trasmapi and sumo: A tool-chain for simulating traffic light control. CoRR, abs/1601.08154, 2016.

[110] I.J.P.M Timóteo, M.R. Araújo, R.J.F. Rossetti, and E.C. Oliveira. Using TraSMAPI for the assessment of multi-agent traffic management solutions. Progress in Artificial Intelligence, 1(2):157–164, may 2012.

[111] F.Y. Wang and S. Tang. A framework for artificial transportation systems: From computer simulations to computational experiments. In Proceedings. 2005 IEEE Intelligent Transportation Systems, 2005., pages 1130–1134. IEEE, 2005.

[112] J. Wahlhe, A.L.C. Bazzan, F. Klügl, and M. Schreckenberg. The impact of real-time information in a two-route scenario using agent-based simulation. Transportation Research Part C: Emerging Technologies, 10(5-6):399–417, oct 2002.

[113] B.C. Silva, A.L.C. Bazzan, G.K. Andriotti, F. Lopes, and D. Oliveira. ITSUMO: An intelligent transportation system for urban mobility. In Innovative Internet Community Systems, pages 224–235. Springer Berlin Heidelberg, 2006.

[114] R.J.F. Rossetti and R. Liu. Advances in artificial transportation systems and simulation. Academic Press, 2014.

[115] A.L.C. Bazzan, M.d.B. do Amarante, G.G. Azzi, A.J. Benavides, L.S. Buriol, L.F.S. Moura, M. Ritt, and T. Sommer. Extending traffic simulation based on cellular automata: From ParticlesTo autonomous agents. In ECMS 2011 Proceedings edited by: T. Burczynski, J. Kolodziej, A. Byrski, M. Carvalho, pages 91–97. ECMS, jun 2011.

[116] MAVS. Agent-based intelligent traffic simulation system, 2015. Last accessed on 2020-05-25.

[117] M. Rym, G. Leask, U. Shakya, and R. Steiner. Architectural Design of the DIVas Environment. In Proceedings of Environments for Multi-Agent Systems (E4MAS04), Columbia University, NY, July 2004.

[118] J. McCarthy. Ascribing mental qualities to machines. Technical report, Stanford University, Department of Computer Science, 1979.

[119] R.I. Brafman and M. Tennenholtz. Modeling agents as qualitative decision makers. Artificial Intelligence, 94(1-2):217–268, 1997.

[120] M. Jakob, Z. Moler, A. Komenda, Z. Yin, A.X. Jiang, M.P. Johnson, M. Pechouček, and M. Tambe. Agentpolis: towards a platform for fully agent-based modeling of multi-modal transportation. In Proceedings of the 11th International Conference on Autonomous Agents and Multiagent Systems-Volume 3, pages 1501–1502. International Foundation for Autonomous Agents and Multiagent Systems, 2012.

[121] M. Čertický, M. Jakob, R. Píbil, and Z. Moler. Agent-based simulation testbed for on-demand mobility services. Procedia Computer Science, 32:808–815, 2014.

[122] J. Hrnčíř and M. Jakob. Generalised time-dependent graphs for fully multimodal journey planning. In 16th International IEEE Conference on Intelligent Transportation Systems (ITSC 2013), pages 2138–2145. IEEE, IEEE, oct 2013.

[123] A. Kesting, M. Treiber, and D. Helbing. Agents for traffic simulation. In Multi-Agent Systems, volume 11, pages 325–356. CRC Press, jun 2009.
[124] M. Treiber, R. Germ, and A. Kesting. From drivers to athletes: Modeling and simulating cross-country skiing marathons. *Traffic and Granular Flow ’13*, pages 243–249, 2015.

[125] M. Treiber and A. Kesting. *Traffic Flow Dynamics*. Springer Berlin Heidelberg, 2013.

[126] J. Görmer and J.P. Müller. Multiagent system architecture and method for group-oriented traffic coordination. In *2012 6th IEEE International Conference on Digital Ecosystems and Technologies (DEST)*, pages 1–6. IEEE, IEEE, jun 2012.