Traffic Simulators

Nadeeshan Dissanayake, Renata Borovica-Gajic, Egemen Tanin,
Shanika Karunasekera

The University of Melbourne, Melbourne, Australia.

1 Synonyms

Traffic simulation software, Transportation simulation software

2 Definition

Traffic simulators are computer programs that model the movement of vehicles (and sometimes pedestrians) through a transportation network over time. These tools can represent real-world traffic flow in a virtual environment, and enable planners and engineers to analyse traffic flow and roadway performance, and test and evaluate traffic management strategies and infrastructure changes before implementing them in the real world. A traffic simulation creates a dynamic 'virtual replica' of traffic conditions, providing means to conduct what-if experiments on scenarios such as new road designs, signal timing plans, or traffic incidents safely and cost-effectively. Modern traffic simulators can model individual vehicle behaviours, capture complex interactions (for example, queue formation and dissipation), and output performance measures such as travel times, speeds, queue lengths, and emissions, under various scenarios. This makes them an important decision-support tool in transportation planning, traffic engineering, and intelligent transportation systems (ITS).

3 Historical Background

Traffic simulation had its origins in the mid-20th century, paralleling advances in computing. The first digital computers in the early 1950s enabled preliminary experiments in simulating traffic. In 1951, researchers at the UK Transport Road Research Laboratory (TRRL) developed one of the first traffic simulations, modelling an intersection. A few years later, computer simulation techniques were applied to highway traffic flow. Throughout the late 1950s, several universities and research groups, especially those with access to early mainframes, began simulating basic traffic phenomena such as car-following behaviour, queue formation at ramps, and simple road networks (Qiao et al. 2021). These early efforts were limited in scope (e.g., considering a single intersection or a highway stretch) but established the feasibility of using computers to mimic traffic behaviour.

By the 1960s, traffic simulation research gained momentum. It became widely accepted that traffic flow theory could be studied via simulation, leading to the development of many foundational models and programs. For example, 1962 saw the creation of traffic simulation software such as NPL, LWEIS, and KELL, followed in 1966 by SIGOP, developed by the Federal Highway Administration (FHWA) to optimise signals through simulation. These developments in the 1960s were largely macroscopic, representing traffic in aggregate terms due to limited computing power. Throughout the 1970s and 1980s, as computers became more powerful and accessible, traffic simulation technology advanced rapidly. Microsimulation of individual vehicles became practical. In 1982, the FHWA introduced TRAF-NETSIM, a microscopic simulator for urban road networks and expressways that represented each vehicle in fine detail. This tool was among the first standardised traffic simulation packages and was part of the FHWA's TRAF family, which later included freeway simulation (FRESIM) and was eventually integrated into CORSIM (Owen et al. 2000; Edward B. Lieberman 2015).

The emergence of object-oriented programming and new languages such as Java allowed simulators to be developed using more flexible and modular approaches. High-Level Architecture (HLA) standards were also introduced to enable interoperability among different types of simulations (Qiao et al. 2021). In the 1990s, graphical user interfaces improved visualisation and easier data handling, supported by the rise of Microsoft Windows and similar platforms, which made simulators more accessible to novice users. Several of the major software packages that are in use today trace their roots to this period, including Paramics (Cameron and Duncan 1996), PTV Vissim (Fellendorf and Vortisch 2010) and Aimsun (Casas et al. 2010). By the end of the 1990s, traffic simulation had evolved from a niche research tool into a mainstream technique in traffic operations and planning, widely adopted by agencies around the world.

Since the early 2000s, traffic simulation software has continued to evolve, gaining new capabilities thanks to improvements in computing power and access to traffic data. Modern simulation models offer higher fidelity in representing driver behaviour and vehicle interactions and can model complex phenomena (e.g., mixed autonomous and human-driven traffic, connected vehicle simulations) that were previously out of reach. Open-source platforms also emerged in the 2000s, expanding access for researchers. Notably, the Simulation of Urban MObility (SUMO) (Alvarez Lopez et al. 2018), initiated in 2001 at the German Aerospace Centre (DLR), has evolved into a highly portable microscopic simulator used globally in research and ITS development.

By the 2010s, the emergence of new technologies such as the Internet of Things (IoT), cloud computing, big data analytics, and autonomous vehicle technology further accelerated simulation advancements. The paradigm of 'simulation-based decision support' became integral to transportation planning, and the concept of 'digital twin' began to link real-time traffic data with simulation models for active traffic management. The growing need to improve the performance of transport networks with the increasing traffic demand, combined with rapid advancements in computing, ensures that simulation software will remain a critical tool well into the future.

4 Scientific Fundamentals

Traffic flow theory provides the foundation for traffic simulation models. Key concepts include the fundamental diagram of traffic (which describes the relationship between flow, density, and speed) and the propagation of traffic waves (e.g., stop-and-go shockwaves). In simulation, these theoretical concepts are operationalised at different levels of detail or modelling resolution.

4.1 Modelling Resolution

In the literature, traffic simulation models are divided into the following four levels of detail (Passos et al. 2011).

Macroscopic models: These treat traffic flow analogously to fluid flow, using aggregated variables. Rather than tracking individual vehicles, macroscopic simulations use equations (often partial differential equations) to describe the evolution of traffic density and volume on road segments. Classic macroscopic models include the Lighthill-Whitham-Richards (LWR) kinematic wave model (1950s) for uninterrupted flow, and queueing models for intersections. These models capture high-level phenomena such as congestion waves and bottleneck capacity but lack detail on individual vehicle behaviours. They are computationally efficient and useful for large-scale network analysis where individual vehicle detail is not required (Chao et al. 2020). Some traffic simulators that support macroscopic models include VISUM (PTV Group 2025a), Aimsun (Casas et al. 2010), TransCAD (Caliper Corporation 2025a), and EMME (Bentley Systems 2025).

Microscopic models: These simulate the behaviour of individual vehicles and drivers. Each vehicle is treated as an agent that follows rules for car-following (i.e., how it accelerates or brakes in response to a leading vehicle), lane-changing, and gap acceptance at merges or intersections.

Microscopic simulation models typically use car-following formulas (e.g., Gipps' model (Gipps 1981), the Wiedemann model, or the Intelligent Driver Model (Treiber et al. 2000)) and rule-based lane-changing logic (e.g., the MOBIL model (Kesting et al. 2007) for lane-change incentives) to govern each vehicle's movements at sub-second resolution. Because they model individual vehicle interactions, microscopic simulations can capture complex local dynamics and produce detailed performance measures, such as delays and queues at specific intersections. However, they require more detailed input (e.g., network geometry, vehicle composition, driver behaviour parameters) and significant computational power for large networks (Chao et al. 2020). The most popular traffic simulators, such as PTV Vissim (Fellendorf and Vortisch 2010), Aimsun (Casas et al. 2010), Paramics (Cameron and Duncan 1996), TransModeler (Caliper Corporation 2025b), SimTraffic (Cubic Transportation Systems 2025), MITSIMLab (Ben-Akiva et al. 2010), and SUMO (Alvarez Lopez et al. 2018), operate at the microscopic level (Su et al. 2024), as they provide the richest level of detail and realism.

Mesoscopic models: These occupy a middle ground between macroscopic and microscopic models. They represent individual vehicles or packets of vehicles but with simplified dynamics. A common mesoscopic approach is the queuing model: vehicles move along links at average speeds until they encounter a queue, then experience delay based on queuing theory (e.g., FIFO queue discharge). Another mesoscopic technique is the gas-kinetic or cluster model, where vehicles are grouped into packets or platoons that move together (Chao et al. 2020). Mesoscopic simulation sacrifices some fidelity in driver behaviour (e.g., it may not simulate individual lane changes) in exchange for faster computation and greater scalability. It is often used for citywide simulations or within hybrid simulation frameworks, where mesoscopic models are applied to uncongested parts of the network, and microscopic models are used in congested hot spots. Tools such as DynaSMART (Mahmassani 2001), Dynemo (Nökel and Schmidt 2002), Dynameq (Mahut and Florian 2010) and Aimsun (Casas et al. 2010) support mesoscopic techniques (Su et al. 2024).

Nanoscopic models: These represent an emerging modelling approach that offers even greater detail than microscopic simulation. Nanoscopic models are primarily used in the field of autonomous driving, where internal functions of vehicles, such as gear shifting or vehicle perception, need to be examined (Passos et al. 2011).

4.2 Time-Step Update vs Event-Driven Update

Under the hood, most traffic simulators use either a time-step (synchronous) update or a discrete-event update to model vehicular interactions and traffic flow. In time-step models (typical of many microscopic simulators), the state of each vehicle is updated in small time increments (e.g., every 0.1 or 0.5 seconds) according to the model rules. Examples of time-step-based simulators include PTV Vissim (Fellendorf and Vortisch 2010) and SUMO (Alvarez Lopez et al. 2018). In event-based models, the simulator jumps in time from one event to the next (e.g., the next possible collision or lane change), which can be more efficient for certain applications. An exemplary event-driven simulator is MATSim (ETH Zürich et al. 2016), which updates the state of the traffic environment dynamically as events occur.

4.3 Stochastic Models vs Deterministic Models

Simulators also vary in how probabilistic events are incorporated. Stochastic models include such realistic driver behaviours (reflecting human variability), whereas deterministic models do not, yielding the same output every time for a given input. Nearly all modern microscopic simulation tools are stochastic, requiring multiple runs and calibrations to match field conditions.

4.4 Action Modelling: Rule-based vs Data-driven

Traditionally, traffic simulation models have been rule-based or model-driven (i.e., built on explicit mathematical models derived from theory or empirical driving behaviour studies). These models include car-following equations, gap acceptance criteria, and lane-change decision logic, which are coded by software developers or engineers. Rule-based models are transparent and interpretable (one can trace why a car slowed down or changed lanes based on the rules), and they allow expert knowledge to be encoded (for example, known car-following behaviour, such as drivers maintaining longer headways at higher speeds). However, because traffic systems and driver behaviours are complex, purely rule-based models may not capture all the realistic behaviour of traffic.

In recent years, there has been a strong trend toward data-driven traffic simulation. With the increasing availability of sensor data (traffic cameras, inductive loops, GPS data, autonomous vehicle logs, etc.), researchers are applying machine learning to "learn" traffic behaviour patterns directly from the data. Data-driven approaches use techniques such as imitation learning (training vehicle agents to imitate real trajectories), reinforcement learning (agents learn driving policies by trial and error to optimise certain objectives), and deep generative models (to synthesise realistic traffic scenarios statistically similar to observations). For example, by mining trajectory datasets or high-resolution vehicle trajectory data (like the NGSIM (U.S. Department Of Transportation Federal Highway Administration 2017) or newer self-driving car datasets), one can train neural network models for car-following that automatically capture human reaction delays or aggressive vs. timid driving styles, which might be difficult to tune in a rule-based model. These learned models can then replace or augment traditional rule-based models in a simulator. Early successes of data-driven simulation include more accurate reproduction of stop-and-go wave patterns and better generalisation to unusual traffic situations (Chao et al. 2020).

Nevertheless, data-driven simulation modelling is still an emerging area and poses challenges. One fundamental issue is validation: ensuring that a simulation driven by learned models reliably reproduces real-world traffic across many scenarios, not just the scenarios it was trained, but also unseen scenarios. Researchers are actively exploring how to evaluate the realism of simulated traffic, for instance, by comparing distributions of traffic metrics or using techniques to distinguish simulated from real trajectory data. Another issue is the need for large datasets. Training advanced models (e.g., deep reinforcement learning models for autonomous vehicles) requires extensive data and computing power. Hybrid approaches are being studied, where core traffic flow principles constrain the machine learning model (to enforce realism, like collision avoidance and physical limits) while still allowing flexibility to fit empirical data (Chen et al. 2024).

4.5 Other Taxonomies

Given the variety of modelling approaches, researchers have proposed other taxonomies to classify traffic simulation models. One approach is by *use-case* domain. For instance, Kang et al. (2019) discusses virtual testing environments and publicly available datasets to test self-driving algorithms. Hu et al. (2024); Zhou et al. (2022); Holen et al. (2022); Kaur et al. (2021) discuss autonomous driving simulators (e.g., CARLA (Dosovitskiy et al. 2017), LGSVL (Rong et al. 2020), AirSim (Shah et al. 2018)), while Ding et al. (2023) also discusses safety-critical driving scenario generation. Silva et al. (2024) examines realistic 3D traffic simulators.

Other use cases include vehicle emission modelling simulators (Madziel 2023), such as PTV Vissim (Fellendorf and Vortisch 2010) and Aimsun (Casas et al. 2010); safety management simulators (Mahmud et al. 2019), including PTV Vissim, Paramics (Cameron and Duncan 1996), and Aimsun; logistics management simulators (Su et al. 2024); traffic management simulators (designed to test ITS strategies and traffic operations in cities); planning-oriented simulators (integrated with travel demand models to forecast long-term scenarios); and research simulators (flexible frameworks used for developing and testing new traffic algorithms). Many simulators began in one niche and later expanded. For example, PTV Vissim started as an academic research tool and later became a commercial product with additional functionality (Edward B. Lieberman 2015).

Wei et al. (2021) divides simulation platforms into three subcategories: *special scene simulation platforms*, which focus on the simulation of specific scenes, including intersections (e.g., FLUIDS (Zhao et al. 2018)); *traffic flow simulation platforms* (e.g., PTV Vissim (Fellendorf and Vortisch 2010), SUMO (Alvarez Lopez et al. 2018)); and *autonomous driving vehicle simulation platforms* (e.g., CARLA (Dosovitskiy et al. 2017), PreScan (Siemens Digital Industries Software 2023), Carsim (Mechanical Simulation Corporation 2025)).

Nguyen et al. (2021) categorizes simulators as *fully agent-based* (e.g., MATSim (ETH Zürich et al. 2016), ITSUMO (Da Silva et al. 2006), MovSim, CARLA (Dosovitskiy et al. 2017), SimMobility), *featuring agent technology* (e.g., ATSim (Chu et al. 2011), FastTrans (Thulasidasan et al. 2009)), and *not agent-based* (e.g., TRANSIMS (Smith et al. 1995), SUMO, PTV Vissim, Paramics), where a simulator is considered fully agent-based when key concepts of the simulation (e.g., travellers, vehicles) are fully implemented as intelligent software agents.

Li et al. (2024) classifies traffic simulators into five main categories: *traffic flow simulators* (e.g., PTV Vissim, Paramics, Aimsun, SUMO, POLARIS (Auld et al. 2016), CityFlow (Zhang et al. 2019)), which model vehicle movements and interactions within road networks; *sensory data simulators* (e.g., AirSim, Sim4CV (Müller et al. 2018), LGSVL, UniSim (Yang et al. 2023)), which generate realistic perception data for sensor-based tasks; *driving policy simulators* (e.g., TORCS (Wymann et al. 2000), MACAD (Palanisamy 2020), Nocturne (Vinitsky et al. 2022), Waymax (Gulino et al. 2023), highway-env (Leurent 2018), SUMMIT (Cai et al. 2020), MetaDrive (Li et al. 2023)), which provide scenarios for developing and testing driving strategies; *vehicle dynamics simulators* (e.g., CarSim, MATLAB (The MathWorks, Inc. 2025), Gazebo (Koenig and Howard 2004)), which replicate vehicle behaviour based on physics; and *comprehensive simulators* (e.g., CARLA, DeepDrive (Deepdrive Team 2025), NVIDIA Drive Sim (NVIDIA Corporation 2025)), which integrate all these functionalities into a single platform.

Due to the emergence of disruptive technologies, such as connected and autonomous vehicles (CAVs) and intelligent intersection management, various new directions in traffic simulation are being actively explored as well. However, it remains unclear whether these developments will establish themselves as key categories within the simulation taxonomy in the coming years.

5 Key Applications

Traffic simulators are applied across a wide range of domains in transportation engineering and research. Below are the primary application areas, along with the relevant types of simulation and prominent software tools used in each context. Modern platforms often overlap in capabilities, but certain tools have historically built strong reputations in specific domains due to their features or accuracy. Table 1 summarises several widely used simulators and their characteristics, while the following sections describe how simulations support various transportation applications.

5.1 Traffic Flow Analysis

Traffic flow analysis is a fundamental application of traffic simulation software, used to study the dynamics of vehicular movement and understand the behaviour of traffic such as congestion, queue formation, and travel delays. Simulators like PTV Vissim, Aimsun, Paramics, CORSIM, and SUMO have long been used to model and analyse traffic flow under different demand and control scenarios (Mubasher and Syed Waqar Ul Qounain 2015; Li et al. 2024). These tools offer valuable insights into transportation networks, allowing for the evaluation of strategies like signal timing adjustments, road expansion projects, and dynamic lane management. Moreover, simulations help quantify key performance indicators such as average speed, vehicle throughput, level of service, and reliability, enabling planners to optimise network efficiency and alleviate congestion-related problems.

5.2 Traffic Safety and Efficiency Analysis

Traffic simulators are crucial tools for analysing and improving road safety by modelling accident-prone scenarios, evaluating safety metrics, and optimising both safety and efficiency in transportation networks. Software platforms such as PTV Vissim, Aimsun, Paramics, Tritone (Giofrè et al. 2013) and SSAM (Pu and Joshi 2008) are widely used to simulate vehicle interactions and assess safety measures, including speed management, intersection design improvements, and implementation of ITS technologies like collision avoidance (Mustapha et al. 2024; Mahmud et al. 2019). Additionally, traffic simulation software supports surrogate safety measures (SSMs) that identify potential collision risks based on vehicle trajectories, providing planners with insights for proactive safety improvements. Importantly, simulations help balance safety objectives with traffic

Table 1 Comparison of Major Traffic Simulation Software

Software	Modelling Scale	Notable Features	Typical Use Cases
PTV Vissim (Germany) (Fellendorf and Vortisch 2010)	Microscopic (vehicle-level); small to medium networks	Highly detailed driver behaviour (Wiedemann model); 3D visualisation; signal controller API (COM interface); multimodal (cars, buses, bikes, pedestrians)	Urban traffic operations; ITS evaluations; consultant studies for intersections & corridors (industry standard for signal optimisation, roundabout analysis, etc.)
Aimsun Next (Spain) (Casas et al. 2010)	Microscopic, Mesoscopic, and hybrid; small to large networks	Multi-resolution simulation (can mix micro & meso in one run); integrated dynamic traffic assignment; supports public transport & pedestrians; rich GUI and scenario management	City-wide traffic management studies; planning (long-term) studies with dynamic assignment; evaluating transit priority and integrated corridor management (used by agencies and researchers alike)
Paramics (UK) (Cameron and Duncan 1996)	Microscopic; small to large networks (via parallel computing)	Fast simulation engine with parallel processing; originally strong 3D graphics; plugin SDK for custom logic; developed as PARallel MICroscopic Simulator	Large network microscopic simulation (early adopter in modelling big cities); research on traffic flow theory; now used in highway agencies for specific projects (though somewhat supplanted by others in popularity)
CORSIM (USA) (Owen et al. 2000)	Microscopic (discrete-event); small to medium networks	Integrates freeway & arterial simulation (FRESIM and NETSIM); built-in actuated signal and stop/yield logic; stochastic, time-step simulation	Traffic engineering analyses in the US (historically used by state DOTs for interchange design, arterial timing); educational use (teaching microscopic simulation basics); limited use today due to older interface
SUMO (Germany) (Alvarez Lopez et al. 2018)	Microscopic (and mesoscopic with add-ons); medium to large networks	Open-source and highly extensible; Traci interface for live control of simulation; supports co-simulation (e.g. with network simulators); multimodal (cars, public transport, pedestrians); can import real maps (OpenStreetMap)	Research and development (connected & autonomous vehicle simulation, algorithm testing); traffic impact studies where cost is a concern; quick prototyping of ITS applications; academic use for coursework (owing to free availability)
MATSim (Switzerland) (ETH Zürich et al. 2016)	Mesoscopic; queue-based simulation; very large networks (city/region)	Agent-based: simulates individual travellers with daily plans; iterative route replanning to reach equilibrium; fast simulation of millions of agents; extensible (open-source)	Transportation planning and policy scenarios at metropolitan scale (road pricing, public transport network design); scenario modelling requiring many simulated travellers (e.g. entire daily activity patterns); not for detailed junction control (mesoscopic traffic model)
CARLA (Spain) (Dosovitskiy et al. 2017)	Microscopic; small to medium networks	Open-source; highly realistic 3D environment; supports sensor suite simulation (cameras, LIDAR, RADAR); flexible API; ROS integration; weather and lighting customisation	Autonomous driving research; development and validation of perception, planning, and control algorithms; training machine learning models for self-driving applications

efficiency goals, enabling planners to develop integrated strategies that reduce both accident rates and congestion.

5.3 Road Infrastructure Design and Evaluation

Traffic simulators are extensively used in the design, testing, and evaluation of road infrastructure projects. By virtually replicating proposed infrastructure changes, such as new intersections, roundabouts, or highway expansions, simulators such as PTV Vissim, Aimsun, Paramics, and SimTraffic enable engineers to anticipate impacts on traffic flow, safety, and network capacity before physical implementation. Simulation outcomes inform critical infrastructure design decisions, helping to avoid costly construction errors and minimise future operational issues. They provide assessments of alternative road designs, guide optimal layout configurations, and assist in the optimisation of constructions to mitigate disruptions. Consequently, traffic simulation significantly contributes to the effective planning, design quality, and performance of road infrastructure projects.

5.4 Urban Traffic Management and Intelligent Transport Systems

Traffic simulators are widely used in urban traffic management and ITS to optimise network operations and reduce congestion in densely populated urban areas. They assist in evaluating a variety of traffic management strategies, including adaptive dynamic lane assignments, ramp metering, traffic signal control, and congestion pricing schemes. Prominent simulation tools like PTV Vissim, Aimsun, and SUMO enable detailed assessments of ITS implementations by replicating realistic traffic conditions, sensor deployments, and infrastructure interactions. Furthermore, simulators help urban planners and traffic engineers predict the impacts of intelligent intersection management and connected vehicle technologies, significantly aiding decision-making processes aimed at enhancing urban mobility, reducing delays, and improving overall transportation system safety and efficiency.

5.5 Autonomous and Connected Vehicle Simulation

The rise of autonomous vehicles (AVs) and connected vehicles (CVs) has opened up new applications for traffic simulation. Since deploying untested AV or CV algorithms on real roads poses safety risks, simulation provides a critical, safe testbed for studying how these vehicles might behave and impact traffic flow. Researchers and automotive companies use simulations to evaluate scenarios involving self-driving cars, such as how traffic throughput changes when a certain percentage of vehicles are autonomous, or how AVs should negotiate merges and intersections in mixed traffic. Simulation allows for the controlled variation of conditions (e.g., the penetration rate of AVs, different driving logics) to assess outcomes like capacity, safety and travel time.

Microscopic simulation is the primary approach for AV/CV studies, as it focuses on individual vehicle behaviour. Simulators such as CARLA, SUMO, MATSim, and PTV Vissim enable the modelling of realistic traffic scenarios involving mixed fleets of human-driven and autonomous vehicles. This allows researchers and developers to analyse complex AV/CV behaviours, including platooning, automated lane-changing, and intersection negotiations (Lach and Svyetlichnyy 2024; Hu et al. 2024; Kang et al. 2019). Additionally, these simulators support the integration of communication protocols (Vehicle-to-Vehicle and Vehicle-to-Infrastructure), sensor data generation, and real-time decision-making processes, all of which are critical for assessing safety, traffic flow impacts, and the overall performance of autonomous transportation systems. As a result, these simulations play a key role in informing policy-making, infrastructure planning, and technological advancements necessary for the successful deployment of AV and CV technologies.

5.6 Public Transport and Shared Mobility

Traffic simulators play a crucial role in optimising public transportation systems and evaluating shared mobility services within urban environments. Simulation software such as PTV Vissim, Aimsun, and Paramics assists transit agencies and urban planners in assessing the effectiveness of dedicated bus lanes, simulating bus routes, implementing transit signal priority strategies, and making scheduling adjustments to enhance public transit reliability and efficiency (Ghariani et al. 2014). Additionally, simulators can support the analysis of emerging shared mobility concepts, including ride-sharing, ride-pooling, and micromobility solutions like bike-sharing and e-scooters. By modelling interactions among various transport modes, such as buses, trams, pedestrians, and shared vehicles, traffic simulators enable a comprehensive evaluation of multimodal transportation networks. This allows planners to balance service quality, operational efficiency, and sustainability goals in urban mobility planning.

5.7 City Logistics and Freight Transport

Traffic simulators play a crucial role in addressing the challenges of urban freight transport by modelling city logistics operations and evaluating freight-related interventions. They enable detailed analysis of delivery strategies, including urban consolidation centres, off-peak deliveries, and dynamic loading zones. Simulations allow urban planners and logistics providers to assess the impacts of freight activities on traffic congestion, road network performance, and emissions, facilitating informed decision-making regarding infrastructure adjustments, regulatory measures, and sustainability initiatives. Moreover, these tools help quantify trade-offs between freight efficiency and broader urban mobility goals, ultimately guiding cities toward more integrated, efficient, and environmentally friendly freight transport systems.

5.8 Environmental Impact Analysis

Traffic simulators are increasingly being used in environmental impact analysis to quantify the ecological effects of transportation activities, particularly in terms of vehicular emissions, noise pollution, and fuel consumption. Simulation tools such as PTV Vissim and Aimsun can accurately model vehicle trajectories, speeds, and acceleration patterns, providing critical data that can be integrated with emission calculation models like MOVES and COPERT (Madziel 2023). These combined simulation frameworks enable transportation planners and environmental analysts to assess the environmental impacts of proposed infrastructure projects, congestion mitigation measures, and traffic management strategies. By simulating various policy scenarios, such as congestion pricing, eco-driving strategies, and traffic signal optimisation, simulators help identify effective interventions to minimise environmental footprints, improve air quality, and support urban sustainability goals.

5.9 Pedestrian and Crowd Behaviour

Traffic simulators are increasingly incorporating specialised capabilities for modelling pedestrian movements and crowd dynamics, which are essential for designing safe and efficient urban environments. Tools such as PTV Viswalk (PTV Group 2025b), Aimsun, Legion (Bentley Systems 2023), Anylogic (The AnyLogic Company 2025), and SUMO (Alvarez Lopez et al. 2018) enable the analysis of pedestrian behaviour at intersections, transit hubs, event venues, and emergency evacuation scenarios (Caramuta et al. 2017). By accurately simulating pedestrian interactions, walking patterns, queuing behaviours, and responses to infrastructure layouts, these tools allow planners and engineers to optimise pedestrian flow, enhance safety, and improve the overall user experience. Furthermore, pedestrian simulations help evaluate the impacts of shared spaces, and crowd management strategies, providing valuable insights for transportation planning and urban design.

5.10 Research and Development

Traffic simulators play a crucial role in research and development within transportation engineering, offering controlled environments to explore new theories, methodologies, and technologies. Simulation tools like SUMO (Alvarez Lopez et al. 2018), PTV Vissim (Fellendorf and Vortisch 2010), CARLA (Dosovitskiy et al. 2017), MATSim (ETH Zürich et al. 2016), SimMobility (Adnan et al. 2016), SMARTS (Ramamohanarao et al. 2016), and MITSIMLAB (Ben-Akiva et al. 2010) allow researchers to develop, test, and validate advanced traffic management algorithms in new settings, innovative vehicle control strategies, and intelligent transport systems before real-world deployment. These simulators enable experimentation in emerging fields such as connected and autonomous vehicles, reinforcement learning-based traffic control, and data-driven mobility modelling. By supporting exploratory analysis, hypothesis testing, and algorithm benchmarking, traffic simulators significantly accelerate technological innovation and contribute to advancements in both transportation research and practice.

6 Future Directions

The field of traffic simulation is evolving rapidly, driven by emerging technologies, new data sources, and shifting transportation paradigms. Several key trends and future directions are currently shaping the next generation of traffic simulation software and research. The following subsections highlight these major areas of development, providing detailed insights into each specific direction.

6.1 Data-Driven and AI-Augmented Simulation

The future of traffic simulation increasingly depends on using data-driven techniques and artificial intelligence (AI) to improve model accuracy, realism, and predictive capabilities. Advances in machine learning, particularly reinforcement learning, imitation learning, and deep learning, are enabling simulators such as SUMO, CARLA, and PTV Vissim to incorporate sophisticated, data-derived behavioural models for vehicles, pedestrians, and connected systems. By integrating real-time traffic data, sensor inputs, and large-scale trajectory datasets, these simulators can adapt dynamically, offering more accurate representations of complex traffic interactions and human decision-making processes. AI-augmented simulations are expected to support real-time traffic management, digital twin development, and traffic forecasting, significantly enhancing transportation planning, policy evaluation, and autonomous vehicle support (Chen et al. 2024; Chao et al. 2020).

6.2 Integration with Real-Time Data and Digital Twins

An important emerging direction for traffic simulators is their integration with real-time data streams to create dynamic, responsive digital twins of transportation networks. Digital twins are virtual replicas of physical systems that enable transportation agencies to continuously monitor, predict, and manage traffic conditions, offering insights and recommendations based on live sensor data, GPS traces, and IoT devices. Simulators such as SUMO are increasingly incorporating functionalities that support real-time synchronisation with actual network conditions, enabling rapid scenario testing and informed decision-making for operations management and emergency response (Zhang et al. 2024; Kušić et al. 2022). As data availability and computational capabilities continue to grow, the development of digital twins is expected to become a foundational element in smart city frameworks, supporting proactive traffic management, infrastructure optimisation, and enhanced urban mobility.

6.3 Support for Connected and Autonomous Vehicles

A critical future direction for traffic simulation software is in line with the advancement of connected and autonomous vehicles (CAVs). As CAVs become more widespread, simulation platforms such as CARLA, SUMO, and PTV Vissim are expected to incorporate increasingly sophisticated features for modelling complex vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) interactions. Future simulators will integrate detailed sensor models, standardised communication protocols, and advanced automation behaviours, creating realistic testbeds for assessing autonomous vehicle performance, mixed traffic dynamics, and cooperative traffic management strategies. Enhancements in scalability and real-time responsiveness will further support comprehensive safety evaluations and policy testing, ultimately enabling informed, data-driven integration of CAVs into modern transportation systems.

6.4 Multi-modal and Novel Mobility Modes

As urban mobility systems continue to evolve and integrate a broader range of transportation modes, future traffic simulators are expected to offer more comprehensive support for multimodal networks and emerging mobility services. This encompasses not only traditional modes such as private vehicles and public transit, but also micro-mobility solutions like e-scooters, shared bicycles, autonomous shuttles, and ride-sharing platforms. Simulation frameworks are increasingly being extended to capture the complex interactions among these diverse modes, incorporating considerations such as first-mile/last-mile connectivity (FMLC), curbside management, and intermodal transfers. By enabling integrated simulations of passenger flows, freight movements, and shared mobility services, next-generation simulators will support urban planners in designing transportation systems that are more sustainable, accessible, and efficient. These capabilities are especially important for evaluating policies aimed at promoting active travel and shared mobility, and for analysing how new modes influence overall network performance and user behaviour.

6.5 Validation, Calibration, and Credibility

As traffic simulations assume an increasingly central role in transportation planning and operational decision-making, ensuring the accuracy and reliability of simulation outcomes is becoming a critical priority. Future research in traffic simulation is expected to place greater emphasis on systematic validation and robust calibration processes, supported by high-resolution traffic data from sensors, connected vehicles, and probe data sources. Techniques such as automated calibration using optimisation algorithms and data assimilation methods will enable simulations to more accurately replicate real-world traffic dynamics. Simulation outputs are not only expected to be accurate but also transparent and reproducible. These advancements are essential for fostering confidence in simulation results, particularly in high-stakes applications such as policy evaluation, infrastructure investment planning, and safety assessments.

6.6 High-Performance Computing

As urban mobility systems become increasingly complex and the demand for large-scale, high-fidelity simulations grows, scalability and high-performance computing are emerging as critical priorities for traffic simulation tools. Future simulators are expected to use parallel computing architectures, distributed simulation frameworks, and GPU acceleration to model extensive metropolitan regions, or even entire national transportation networks, at microscopic resolution. Scalability is especially vital for applications such as digital twins, real-time traffic management, and multi-agent autonomous vehicle simulations, where thousands or even millions of entities must be simulated concurrently with high temporal precision. These advancements will empower transportation researchers and practitioners to perform more comprehensive scenario analyses, incorporate stochastic variability, and conduct ensemble simulations to support robust and data-driven decision-making.

6.7 Integration with Smart Cities

Recent developments in traffic simulators are closely intertwined with the broader development of smart city initiatives, in which integrated data platforms and interconnected systems enable holistic urban management. Future traffic simulation tools are expected to interface seamlessly with smart city frameworks, combining traffic models with energy grid simulations, land-use planning tools, parking management systems, environmental monitoring systems, and public health data. By linking mobility simulations with real-time inputs from IoT devices, environmental sensors, and energy management infrastructure, urban planners can gain multidimensional insights that support sustainable city development. For instance, integrating traffic simulations with electric vehicle (EV) charging infrastructure models allows for the assessment of charging demand impacts on both mobility patterns and energy networks. To support such interoperability, simulators are increasingly adopting open application programming interfaces (APIs) that enable comprehensive analysis across transportation, energy, environmental, and policy domains. These integrated platforms will empower cities to evaluate complex trade-offs and synergies, ultimately supporting the development of efficient, and sustainable urban ecosystems.

6.8 User Experience

Enhancing user experience is becoming an increasingly important focus in the future development of traffic simulation tools, to make these complex systems more accessible, intuitive, and effective for a broader range of users. Traditionally, traffic simulators have required significant technical expertise to configure models, interpret results, and integrate external data sources. However, recent advancements are prioritising improved graphical user interfaces (GUIs), featuring drag-and-drop scenario builders, real-time visualisations, and interactive dashboards. Commercial tools such as Aimsun Next and PTV Vissim already offer user-friendly scenario management environments, while open-source platforms like SUMO are progressively incorporating streamlined configuration tools, enhanced visualisation options, and more comprehensive documentation to lower the barrier to entry. These improvements not only increase productivity for expert users but also empower decision-makers, educators, and non-specialist stakeholders to participate more actively in transportation planning and policy evaluation.

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