Analysis, Modeling, and Simulation (AMS) for Intelligent Transportation Systems (ITS) State of Research

AMS for ITS State of Research

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16. Abstract

The purpose of this document is to summarize for the United States Department of Transportation's (U.S. DOT's) Intelligent Transportation Systems (ITS) Joint Program Office (JPO) Analysis, Modeling, and Simulation (AMS) Program, the state of research for AMS for ITS tools. The AMS for ITS Program seeks to capture the state of research for AMS for ITS tool use that is representative of the exploratory, investigative, and developmental work, and not considered work typically in practice, with the understanding that a fully exhaustive survey of the research community is not feasible. A literature review as well as discussions with a volunteer group of expert stakeholders on AMS for ITS tools being developed through and used in research were conducted. The identified tools have been categorized and documented in this report. Furthermore, this report captures a summary of key findings for each tool. Key findings include the advantages of the currently used tools and gaps/challenges researchers may encounter when applying these tools as well as developing, adopting, and/or employing more advanced AMS for ITS tools. It is important to understand the research needs to support traffic analysis tools (TAT) and other AMS for ITS tool strategies and projects. For example, these needs may include development of guidance, use cases, datasets, data exchanges, algorithms, policy, pilot deployments, evaluations, and professional capacity building. Findings from this report are part of the foundational analyses for the program plan development for AMS for ITS Program.

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Executive Summary

The purpose of this document is to summarize for the United States Department of Transportation (U.S. DOT) Intelligent Transportation Systems (ITS) Joint Program Office (JPO) Analysis, Modeling, and Simulation (AMS) Program, the state of research for AMS for ITS tools. The AMS for ITS Program seeks to capture the state of research for AMS for ITS tool use that is representative of the most relevant exploratory, investigative, and developmental work, and not considered work typically in practice. This state of research report does not include a fully exhaustive survey of the research community, as that is not feasible, but does attempt to capture a representative snapshot. A literature review and interviews with expert stakeholders who utilize and/or develop AMS for ITS tools in research were conducted. The identified tools have been categorized and documented in this report. Furthermore, this report captures a summary of key findings for each tool. Key findings include the advantages of the currently used tools and gaps/challenges researchers may encounter when applying these tools as well as developing, adopting, and/or employing more advanced AMS for ITS tools. It is important to understand the research needs to support traffic analysis tools (TAT) and other AMS for ITS tool strategies and projects. For example, these needs may include development of guidance, use cases, datasets, data exchanges, algorithms, policy, pilot deployments, evaluations, and professional capacity building. Findings from this report are part of the foundational analyses for the program plan development for the ITS JPO's AMS for ITS Program.

Approach

A multifaceted approach was used to develop this state of research report. The approach included: (1) a review of existing literature on AMS for ITS tools, and (2) a series of discussions with a volunteer group of expert stakeholders from state, local, and regional agencies and consultants, vendors/tool developers, and academic researchers who are conducting research in the area of AMS for ITS tools. This two-pronged approach ensured that relevant pieces of information are captured in this report and that representative gaps and challenges experienced by researchers are identified. Additionally, a qualitative assessment of the potential positive impacts that may be experienced by the state of research for AMS for ITS tools vs. the potential difficulties the ITS JPO's AMS for ITS Program would face if the Program were to work on mitigating or solving the identified gaps/challenges was conducted. This analysis led to a prioritization of the gaps/challenges to help guide program plan development based on feedback from an activity conducted with the project team and federal stakeholder AMS for ITS subject matter experts (SMEs).

Summary of AMS for ITS Tools Used in Research

Tools that are used to perform analysis, modeling, and/or simulation that include at least one ITS component (e.g., ITS strategy, technology, data) and are considered part of the state of research were included in this report. A total of 20 AMS for ITS tools were identified and assessed. Most of these tools fall within at least one of the seven Federal Highway Administration (FHWA) TAT categories, which are sketch planning; travel demand models; analytical/deterministic; traffic optimization; macroscopic simulation; mesoscopic simulation; and microscopic simulation. The category with the highest number of tools is microscopic simulation. Information regarding the following areas was captured for each of the identified AMS for ITS tools: tool description; tool category(ies); primary purpose(s)/objective(s); scope; data inputs/requirements; performance measures; known entities that use/enhance the tool and select research use cases; and a summary of key findings from the review of the tool, including advantages and gaps/challenges in regard to researcher use. For each tool category, except for the "Other" tool category due to the differing natures of the tools, fidelity and/or resolution are discussed. Within the "Other" tool category, fidelity and/or resolution are captured for each tool. Additionally, interviews were conducted with 20 stakeholders representing 15 organizations ranging from public transportation agencies to consultants to tool developers to academic researchers. Most tools that the stakeholders identified as ones they use are included in the literature review. However, some of the tools they mentioned are in-house, specific to their organization, do not incorporate any ITS components, or are still under development/new and do not yet have publications/documentation yet associated with their development/utilization in research.

The following insights regarding the state of research on AMS for ITS tools were found based on the literature review and interviews with stakeholders:

- There are a number of tools that are used both in practice and research. In practice, they tend to be utilized as intended, leveraging their default capabilities. In research, these tools may be used as intended to analyze, model, and/or simulate inputs from other research-developed tools or to generate outputs to be further analyzed via other research-developed tools to address research problems. Additionally, in research, these tools' functionalities/capabilities may be extended or enhanced through Application Programming Interfaces (APIs) and Software Development Kits (SDKs) to address research problems.
- A variety of AMS for ITS tools are used in and/or developed through research and most align well with the TAT categories. The majority of the identified tools used in research are high-fidelity microscopic simulation ones that are used for operational, control, design, planning, and evaluation for ITS strategies, applications, and technologies.
- Mobility and environmental impact performance measures are the most prevalent outputs from research AMS for ITS tools, while fewer tools output safety-specific measures. Interviewed researchers noted a need to better model safety impacts and use straightforward, easy to understand, and agreed upon measures to assess all types of objectives.

- Even though less than half of the reviewed tools have multiresolution modeling (MRM) capabilities, the interviewed researchers reported that they are performing an increasing amount MRM with an emphasis on real-time hybrid modeling.
- Artificial intelligence (AI)/machine learning (ML) techniques and algorithms are becoming more prevalent in AMS for ITS tools used in research for purposes such as enhancing demand and choice modeling, performing vision-based detection, modeling/improving modeling of the movements/behaviors of connected and automated vehicles (CAVs), leveraging, cleaning, analyzing, and/or fusing large datasets for improved data-driven transport planning and policymaking, etc. However, researchers noted that these advanced techniques can be misused and difficult to interpret.
- Researchers utilize a mix of historical and/or real-time in-house field collected data, in-house simulator collected/generated data, open-source data (e.g., OpenStreet Map, National Performance Management Research Data Set [NPMRDS], state DOTs, Next Generation Simulation [NGSIM]), and/or proprietary data that are purchased or accessed through partnerships (e.g., INRIX, StreetLight Data, Wejo, Veraset, SafeGraph) to develop, train, calibrate, test, validate, enhance, and/or use AMS for ITS tools.

Key Findings

Eleven (11) gaps/challenges were identified and consolidated based on the state of research for AMS for ITS tools obtained from the representative but non-exhaustive literature review; and set of researcher stakeholder interviews. A qualitative analysis of these gaps/challenges was conducted in terms of the potential positive impact researchers might experience and potential difficulties that would be faced by the ITS JPO's AMS for ITS Program if the Program were to pursue mitigating or solving them. This analysis will be used in conjunction with the analysis from the concurrent State of Practice for AMS for ITS report to help guide the AMS for ITS Program goals, objectives, and activities. Findings from this report and the qualitative analysis indicate that the AMS for ITS Program may be best positioned to initially focus on the following gaps/challenges with medium to high positive impacts and medium to low levels of difficulty to address:

- **Gap/Challenge 3:** Lack of guidance for how to promote and facilitate adoption of research-developed AMS for ITS tools and methods with state agencies and practitioners.
- **Gap/Challenge 6:** Uncertainty for how agencies and researchers can/should handle, store, utilize, process, and/or incorporate emerging ITS (big) data with their AMS tools; lack of enough standards and engagement with standards for ITS data.
- **Gap/Challenge 7:** Lack of an AMS for ITS best practices clearinghouse.
- **Gap/Challenge 8:** Lack of an open data hub specifically for AMS for ITS data.
- **Gap/Challenge 9:** Lack of an open, easily accessible connected AMS for ITS tool development environment where multiple researchers at various locations can collaborate and interface with other software.

- **Gap/Challenge 11:** Significant CPU/GPU and storage requirements needed to run AMS tools.

1 Introduction

1.1 Background

Analysis, Modeling, and Simulation (AMS) are core competencies in the field of transportation engineering. Analysis involves examining and interpreting data information, or systems quantitatively and/or qualitatively to gain insights, identify patterns, and draw conclusions. Modeling is the process of creating representations of real-world systems and/or processes to evaluate hypothetical scenarios, understand complex interactions, and predict outcomes. Simulation uses computational models under controlled conditions to emulate behaviors and interactions of real-world systems and/or processes to generate artificial scenarios and study system behavior over time. AMS enable engineers and other practitioners to safely test strategies and technologies prior to field deployment, gain insights into potential investment solutions, and optimize currently employed operations and control strategies. Practitioners can iteratively test hypotheses, assess impacts, and select optimal strategies and alternatives. Decision makers can make more informed investment decisions. AMS can be a critical element in decision-making in an increasingly complex, dynamic transportation systems ecosystem where planning under uncertain conditions is a compelling need. New questions are arising regarding the impacts of commonly used in practice and research-emerging intelligent transportation systems (ITS) technologies and strategies, such as artificial intelligence (AI)/machine learning (ML), vehicle connectivity and automation, shared mobility, mobility as a service (MaaS), and electric vehicles (EVs). Transportation planners foresee increasingly complex scenarios regarding transportation options to address vulnerable road users (VRUs) and accessibility, equity, and climate change.

The U.S. DOT plays a critical role in providing public agencies with the necessary AMS tools and guidance to make the best possible investment decisions. For example, the U.S. DOT has a history of taking effective, coordinated, and comprehensive actions to create and improve traffic analysis tools (TAT) for traffic operations analysis. With new infrastructure development and emerging technologies, there is a need for the U.S. DOT to have a more seamless collaboration among different modes at the federal level as well as comprehensive understanding of practical needs from state and local agencies. For example, representing emerging technologies in TAT remains a nascent field. Tools for applying cutting-edge research and understanding road user behavior in relation to ITS technologies are still being advanced, and the benefits (and costs) to state and local infrastructure owners and operators (IOOs) are unclear. These uncertainties limit the confidence such entities have in integrating ITS in their planning and policy processes as well, especially with the need to prioritize projects competing for finite resources. In addition, the Complete Streets concept promoted by U.S. DOT considers the safety of all road users to achieve the creation of safe, connected, and equitable street networks. This will change the objectives, performance measures, and benefit assessments of current AMS tools. To bring these various elements into focus, identify their logical connections and dependencies, and address gaps with new projects leading to comprehensive solutions, the ITS JPO requires a holistic AMS for ITS program plan and accompanying roadmap. However, before a program plan can be developed, foundational analyses must be conducted to better understand the current state of the field and identify gaps/challenges this program may be able to fill/mitigate. In this report, a gap refers to the difference between current conditions and/or capabilities and desired expectations and/or capabilities. A challenge refers to an obstacle or difficulty that needs to be overcome to achieve a desired outcome.

1.2 Purpose

The purpose of this document is to summarize for the U.S. DOT ITS JPO's AMS for ITS Program, the state of research for AMS for ITS tools to understand the current capabilities as well as identify opportunities for the AMS for ITS Program to address challenges and bridge gaps. Examples of research needs that could help address the identified gaps and challenges may include methodologies/algorithms and use cases, datasets/data exchanges, guidance, policy, pilot deployments, evaluations, and professional capacity building activities. The AMS for ITS Program seeks to capture the state of research of AMS for ITS tool use that is representative of the exploratory, investigative, and developmental work to support AMS, and not considered work typically in practice, knowing that an exhaustive survey of the research community is not feasible.

For this report, a method (or methodology) is a structured approach or framework used to solve problems, conduct research, or achieve specific outcomes by providing guidelines, procedures, and techniques for performing tasks, making decisions, or implementing strategies. A tool is a tangible resource (e.g., physical object, software or code application, or conceptual framework) used to perform specific tasks or achieve a specific objective efficiently and effectively. Methods provide the structured approaches, techniques, and procedures for conducting AMS and tools serve as mediums or conduits through which AMS are conducted by providing the necessary functionality, interfaces, and capabilities.

Note that there is a State of Practice report, titled "*Analysis, Modeling, and Simulation (AMS) for Intelligent Transportation Systems (ITS) State of Practice*", which complements this State of Research report. Although both reports focus on AMS for ITS tools, the State of Practice report's scope is limited to AMS for ITS tools typically used in practice by states, localities, and regional transportation agencies/organizations.

1.3 Document Scope

The scope of this document is limited to AMS for ITS tools' use for and development through research, which encompasses exploratory, investigative, and developmental AMS work that is not typically considered part of common practice. AMS for ITS in the context of this document and the AMS for ITS Program as a whole means that at least one ITS component (e.g., ITS technology capabilities, ITS operational strategies such as integrated corridor management (ICM) and active transportation and demand management (ATDM), connected vehicle communications, data collected from an ITS sensor [some examples include closed-circuit television (CCTV) video cameras, traffic loop detectors, sensors that measure/detect road conditions, surface weather, vehicle emissions, etc. as described in the ITS Roadway Equipment from The National ITS Reference Architecture, Architecture Reference for Cooperative and Intelligent Transportation (ARC-IT) version 9.2 [1]], improvement of a traffic operational/control strategy with advanced analysis techniques, etc.) within the realm of surface transportation is incorporated. Further details regarding AMS for ITS in terms of the report scope are provided below.

1.3.1 ITS and Analysis, Modeling, and Simulation

ITS is a system of innovative technologies and operational strategies that, when integrated and managed, enhance the capabilities of agencies/entities to deliver services aimed at improving the performance of the overall transportation system. In other words, ITS aims to improve transportation by incorporating innovative information and communications-based technologies (ICT) into infrastructure, vehicles, and personal devices. [2]

ITS encompasses a wide range of technologies at different stages of development and readiness for deployment. A typical ITS development process starts with foundational, emerging research that eventually transitions to commonplace practice. Additionally, ITS that are part of commonplace practice may be improved upon/iterated through further research. This means that a broad spectrum of ITS exists that includes highly developed, well understood technologies (e.g., loop detectors) and technologies in lower stages of development with at most limited pilots/deployments, usually in controlled settings (e.g., Society of Automotive Engineers [SAE] Level 4 and/or Level 5 automated vehicles [AV]).

More established ITS technologies have been successfully deployed and managed for years (even decades) and have a solid reputation and usage amongst practitioners. Further examples of such technologies include traveler and transit information systems, dynamic real-time routing, electronic toll collection, ramp metering, and traffic signal management systems. While advances continue to be made with these ITS components, they have a baseline of being adopted in practice by numerous transportation agencies across the U.S. and benefits, costs, and lessons learned have been well documented (see the ITS Deployment Evaluation website) [3].

The other end of the spectrum includes technologies still under development at the research-level that have not been adopted/employed as part of typical practice yet. Further examples of such technologies include connected vehicles (CV), connected and automated vehicles (CAV), cooperative driving automation (CDA), shared mobility, MaaS, etc., and the corresponding communications as well as the incorporation of advanced analysis techniques (e.g., ML) for operational strategy improvements and cybersecurity protection. While pilot deployments have been successfully completed for some emerging ITS, there are still extensive research and development efforts needed before these ITS components are considered ready for adoption/integration in common practice.

Numerous ITS strategies and technologies also exist between these two ends of the spectrum. These may take a commonly used ITS technology/strategy/application and supplement this with emerging ITS methods to manage a transportation system in a novel way. For example, data collection and analysis methods can leverage diverse sensing technologies (e.g., loop detectors, cameras, probes), data fusion, and advanced AI/ML algorithms to improve control strategies and/or investment decision making.

For further information, refer to ARC-IT version 9.2. The Physical Objects (major physical parts of the ITS Architecture) and Functional Objects (building blocks of Physical Objects based on functionality in deployment) help identify and define both traditional and emerging ITS components, as ITS is continuously evolving. [1]

Tools that include the analysis, modeling, and/or simulation of at least one aspect of ITS are within the scope of this report.

1.4 Approach

A multifaceted approach was used to develop this state of research report. The approach included: (1) a review of existing literature on AMS for ITS tools, and (2) a series of discussions with a volunteer group of expert stakeholders from state, local, and regional agencies and consultants, vendors/tool developers, and academic researchers who are conducting research in the area of AMS for ITS tools. This two-pronged approach ensured that relevant pieces of information are captured in this report. Based on the findings from the literature review and the stakeholder interviews, 11 key gaps and challenges were identified. These gaps and challenges were then qualitatively assessed using an analysis of the potential positive impacts for researchers vs. potential difficulties the ITS JPO's AMS for ITS Program may encounter in trying to mitigate and/or solve them.

1.5 Organization of Report

This report is organized as follows:

- **Chapter 1 Introduction** – provides an overview of the AMS for ITS State of Research report, including relevant background information, purpose, scope, and approach.
- **Chapter 2 Glossary and Acronyms** – presents tables defining specific terms and acronyms used throughout the report.

- **Chapter 3 Review of AMS for ITS Tools Used in Research** – summarizes AMS for ITS tools being developed through/used in research and the corresponding gaps and challenges.
- **Chapter 4 Stakeholder Feedback** – summarizes the findings from discussions with the volunteer group of expert stakeholders.
- **Chapter 5 Gaps and Challenges in AMS for ITS Tools Used in Research** – summarizes the gaps and challenges in AMS for ITS tools developed through/used in research based on the literature review and stakeholder inputs.
- **Chapter 6 Conclusions –** presents the conclusions, including key findings from the literature review and stakeholder interviews and potential opportunities for the AMS for ITS Program to address identified gaps and challenges for AMS for ITS tools being developed through and used in research.
- **Chapter 7 References** – lists the references used to develop this report.
- **Appendix A** – presents a summary table from the literature review of the identified AMS for ITS tools being developed through and used in research.
- **Appendix B** – presents the topics/questions discussed with the interviewed researcher stakeholders as well as the research-specific questions/topics discussed with the practitioner and tool developer stakeholders.

2 Glossary and Acronyms

2.1 Glossary

Table 1 defines specific terms used throughout this report. Note that since there are some variations in terminology use within the AMS for ITS community, the table below employs existing resources (e.g., from Society of Automotive Engineers (SAE) standards, FHWA, ITS JPO, etc.) and other related work, as needed.

Table 1. Glossary

Term	Definition
Analysis	Analysis involves examining and interpreting data information, or systems quantitatively and/or qualitatively to gain insights, identify patterns, and draw conclusions.
Automated Vehicle (AV)	Any vehicle equipped with driving automation technologies (as defined in SAE J3016) [4]. This term can refer to a vehicle fitted with any form of driving automation. (SAE Level 1–5), (U.S. DOT AV 3.0) as vehicles in which at least one element of vehicle control (e.g., steering, speed control) occurs without direct driver input [5]. SAE J3016 defines a taxonomy for driving automation ranging from no automation (Level 0) to full driving automation (Level 5) [4].
Capability Maturity Models (CMM)	A development model that aims to improve existing software development processes and assesses the ability of implementing a contracted software project.
Challenge	A challenge refers to an obstacle or difficulty that needs to be overcome to achieve a desired outcome.
Connected and Automated Vehicle (CAV)	A connected vehicle with some level of vehicle automation.
Connected Vehicle (CV)	Connected vehicles communicate wirelessly with each other, with infrastructure, and with wireless devices to share vital transportation information. Connected vehicles use this information to attain 360-

Term	Definition
	degree awareness of nearby vehicles, which increases the driver's situational awareness of their surroundings.
Dedicated Short Range Communications (DSRC)	A communications protocol developed to address the safety critical issues associated with sending and receiving data among vehicles and between moving vehicles and fixed roadside access points. These provide low-latency data-only V2V and V2I communications [6]. In the US, DSRC operates in licensed wireless spectrum in the 5.9 GHz band [7].
Environment	The circumstances, objects, and conditions that surround a system to be built; includes technical, political, commercial, cultural, organizational, and physical influences as well as standards and policies that govern what a system must do or how it will do it.
Fidelity	Fidelity is the accuracy or degree to which the tool represents measurable real-world behaviors, states, perceptions, etc. and resolution is the level of detail that the tool incorporates to represent the real-world.
Gap	A gap refers to the difference between current conditions and/or capabilities and desired expectations and/or capabilities.
Intelligent Transportation Systems (ITS)	ITS is a system of innovative technologies and operational strategies that, when integrated and managed, enhance the abilities and performance of the overall transportation system.
Macroscopic	Macroscopic simulation models are based on the deterministic relationships of the flow, speed, and density of the traffic stream. The simulation in a macroscopic model takes place on a section-by-section basis rather than by tracking individual vehicles. Macroscopic simulation models were originally developed to model traffic in distinct transportation subnetworks, such as freeways, corridors (including freeways and parallel arterials), surface-street grid networks, and rural highways [8].
Mesoscopic	Mesoscopic models combine the properties of both microscopic (discussed below) and macroscopic simulation models. As such, mesoscopic models provide less fidelity than microsimulation tools, but are superior to the typical planning analysis techniques [8].

Term	Definition
Method/Methodology	A method (or methodology) is a structured approach or framework used to solve problems, conduct research, or achieve specific outcomes by providing guidelines, procedures, and techniques for performing tasks, making decisions, or implementing strategies.
Microscopic	Microscopic simulation models simulate the movement of individual vehicles based on car-following and lane-changing theories. These models are effective in evaluating heavily congested conditions, complex geometric configurations, and system-level impacts of proposed transportation improvements that are beyond the limitations of other tool types. However, these models are time consuming, costly, and can be difficult to calibrate [8].
Modeling	Modeling is the process of creating representations of real-world systems and/or processes to evaluate hypothetical scenarios, understand complex interactions, and predict outcomes.
Model Chain	A flow chart that guides the model development process.
Multiresolution Modeling (MRM)	MRM is an integrated modeling approach that allows for the joint application of multiple transportation analysis tools with varying temporal and spatial resolutions (i.e., macroscopic, mesoscopic, and microscopic simulation) to solve a single question or set of questions. Three subcategories of MRMs are full MRMs, partial MRMs, and hybrid models. Full MRMs incorporate macroscopic, mesoscopic, and microscopic models into one framework for modeling, whereas partial MRMs only incorporate two of the modeling resolutions into a single framework. Both full and partial MRM frameworks use an offline approach where one resolution’s model is run until it reaches convergence, then its results are fed into another resolution’s model as inputs. Hybrid models operate in what is considered an online environment, where multiple resolutions’ models are run/simulated concurrently on a rolling time horizon and during which real-time information (i.e., network) is exchanged [9], [10], and [11].
Peak Spreading	Peak spreading is the tendency for travelers to change the time they make their journeys as travel conditions deteriorate.
Practice	What is commonly done or performed by transportation agencies and other transportation engineering, planning, policymaking, etc. practitioners.

Term	Definition
Research	Exploratory, investigative, and developmental work to support AMS for ITS, and not considered work typically in practice.
Resolution	Resolution is the level of detail that the tool incorporates to represent the real-world.
Simulation	Simulation uses computational models under controlled conditions to emulate behaviors and interactions of real-world systems and/or processes to generate artificial scenarios and study system behavior over time.
Technology Readiness Levels (TRL)	Technology Readiness Levels are a method for estimating the maturity of technologies during the acquisition phase of a program. TRLs enable consistent and uniform discussions of technical maturity across different types of technology [12].
Tool	A tool is a tangible resource (e.g., physical object, software or code application, or conceptual framework) used to perform specific tasks or achieve a specific objective efficiently and effectively.

2.2 Acronyms

Table 2 defines acronyms used throughout this report.

Table 2. Acronym List

Acronym	Definition
AADT	Annual Average Daily Traffic
ABM	Activity-Based Model
ADS	Automated Driving Systems
AI	Artificial Intelligence
Aimsun	Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks
AMS	Analysis, Modeling, and Simulation
API	Application Programming Interface
ARC-IT	Architecture Reference for Cooperative and Intelligent Transportation
A-STEP	Achieving Sustainable Train Energy Pathways

Acronym	Definition
ATDM	Active Transportation and Demand Management
ATIS	Advanced Traveler Information Systems
ATMS	Advanced Traffic Management Systems
ATSPM	Automated Traffic Signal Performance Measures
AV	Automated Vehicle
BEAM CORE	Behavior, Energy, Autonomy, and Mobility Comprehensive Regional Evaluator
BSM	Basic Safety Messages
Caltrans	California Department of Transportation
CAMs	Cooperative Awareness Messages
CARLA	Car Learning to Act
CAV	Connected and Automated Vehicle
CBI	Congestion and Bottleneck Identification
CCTV	Closed-Circuit Television
CDA	Cooperative Driving Automation
CMM	Capability Maturity Model
CPU	Central Processing Unit
CRM	Coordinated Ramp Metering
CV	Connected Vehicle
DCFC	Direct Current Fast Charging
D2RL	Dense Deep-Reinforcement-Learning
DEMOS	Demographic Microsimulation
DMS	Dynamic Message Sign
DOE	Department of Energy
DSRC	Dedicated Short Range Communications
DSS	Decision Support System
DTA	Dynamic Traffic Assignment
DynaMIT	Dynamic Network Assignment for the Management of Information to Travelers
E2E	End-to-End
EV	Electrical Vehicle
eVMT	Electric Vehicle Miles Traveled
FHWA	Federal Highway Administration

Acronym	Definition
ft	Feet
GHG	Greenhouse Gas
GIS	Geographic Information System
GISDK	GIS Developer's Kit
GPS	Global Positioning System
GPU	Graphics Processing Unit
GTFS	General Transit Feed Specification
GUI	Graphical User Interface
HCM	Highway Capacity Manual
HCS	Highway Capacity Software
HFN	Hierarchical Flow Network
HOT	High Occupancy Toll
HOV	High Occupancy Vehicle
hr	Hour
I2I	Infrastructure-to-Infrastructure
ICM	Integrated Corridor Management
ICT	Information and Communications-based Technologies
IOO	Infrastructure Owners and Operators
ITS	Intelligent Transportation Systems
JPO	Joint Program Office
km	Kilometer
KNN	K-Nearest Neighbor
kWh	Kilowatt-hour
LBNL	Lawrence Berkeley National Laboratory
LBS	Location-Based Services
LEZ	Low Emission Zone
LOS	Level of Service
LRT	Light Rail Transit
LSTM	Long Short-Term Memory
MaaS	Mobility as a Service
MATSim	Multi-Agent Transport Simulation
mi	Mile

Acronym	Definition
min	Minute
MIT	Massachusetts Institute of Technology
MITSIMLab	MIcroscopic Traffic SIMulation Laboratory
ML	Machine Learning
MOE	Measure of Effectiveness
MOTION	MObility Technology Interstate Observation Network
MOVES	Motor Vehicle Emissions Simulator
mph	Miles Per Hour
MRM	Multiresolution Modeling
MSA	Metropolitan Statistical Areas
NeXTA	Network eXplorer for Traffic Analysis
NGSIM	Next Generation Simulation
NPMRDS	National Performance Management Research Data Set
NREL	National Renewable Energy Laboratory
NYSDOT	New York State Department of Transportation
O-D	Origin-Destination
ODOT	Ohio Department of Transportation
OSM	OpenStreetMap
OSM2GMNS	OpenStreeMap to General Modeling Network Specification
OSS	Open-Source Software
PDM	Probe Data Messages
PeMS	Performance Measurement System
PMT	Passenger Miles Traveled
POI	Point of Interest
R&D	Research and Development
RITIS	Regional Integrated Transportation Information System
RM3P	Regional Multi-Modal Mobility Program
RSE	Roadside Equipment
RSG	Resource Systems Group
SAE	Society of Automotive Engineers
SDK	Software Development Kit
sec	Second

Acronym	Definition
sec/veh	Seconds Per Vehicle
SME	Subject Matter Expert
SOC	State of Charge
SP	Stated Preference
SPaT	Signal Phase and Timing
SST	Software Selection Tool
SUMO	Simulation of Urban Mobility
SVM	Support Vector Machine
TAT	Traffic Analysis Tools
TCA	Trajectory Conversion Algorithm
TMC	Transportation Management Center
TNC	Transportation Network Company
TRANSIMS	Transportation Analysis and Simulation System
TRL	Technology Readiness Level
TSIS	Traffic Software Integrated System
U.S. DOT	United States Department of Transportation
USGS	United States Geological Survey
v/c	Volume to Capacity
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VANET	Vehicular Ad-hoc Network
VDOT	Virginia Department of Transportation
veh	Vehicle
veh/ln/mi	Vehicles Per Lane Per Mile
VHT	Vehicle Hours Traveled
VMS	Variable Message Sign
VMT	Vehicle Miles Traveled
VOICES	Virtual Open Innovation Collaborative Environment for Safety
VR	Virtual Reality
VRU	Vulnerable Road User

3 Review of AMS for ITS Tools Used in Research

This chapter presents an overview of the representative review of exploratory, investigative, and developmental AMS for ITS tools used in research. The identified tools are organized into categories, as defined in the *Traffic Analysis Toolbox Volume II: Decision Support Methodology for Selecting Traffic Analysis Tools* [13]. These principal tool categories include sketch planning; travel demand models; analytical/deterministic; traffic optimization; macroscopic simulation; mesoscopic simulation; and microscopic simulation. An additional "Other" principal category is used when the ones specified above are not applicable. **While tools may fall within multiple categories, the one most applicable to the tool (in terms of its use in research) is used in the organization of this section and any other applicable ones will be noted in the "Tool Category(ies)" sub-section specific to the tool**.

Based on feedback and findings from the stakeholder interviews and literature review from the State of Practice report for AMS for ITS, the principal categories identified in the preceding paragraph may need to be further refined to reflect the most accurate and relevant groupings of the AMS for ITS tools both used in practice and developed through and used in research. This tool categorization refinement is essential to enabling optimal understanding of the findings from this state of research report as well as those from the concurrent State of Practice report. Furthermore, these categories will help identify options for how the identified opportunities to address current and future gaps and challenges will be translated into subsequent AMS for ITS Program activities as the program plan is developed and implemented. Further refinement of the AMS for ITS tool categories is also expected to occur during the program plan development process, specifically based on findings during additional stakeholder input/feedback events.

For each tool category, except for the "Other" tool category due to the differing natures of the tools, Fidelity and/or Resolution are discussed. Within the "Other" tool category, Fidelity and/or Resolution are captured for each tool. Fidelity is the accuracy or degree to which the tool represents measurable real-world behaviors, states, perceptions, etc. and resolution is the level of detail that the tool incorporates to represent the real-world [9]. For each tool, the following information is captured:

- **Tool Description:** An overview of the tool, including if a tool is activity-based and/or agent-based, if applicable.
- **Tool Category(ies):** The principal category as well as any other categories that are applicable to the tool (e.g., if a tool used primarily for microscopic simulation in research also has the capability to perform mesoscopic simulation, that will also be listed in this section).

- **Primary Purpose(s)/Objective(s):** How the tool is used in general and what specifically the tool aims to achieve.
- **Scope:** The breadth of transportation mode/road user types, transportation facilities and road types, etc. as well as ITS components for which the tool may be applicable.
- **Data Inputs/Requirements:** What types of data, data formats, amounts of data, etc. need to be provided to use the tool, as they are available.
- **Performance Measures/Outputs:** Output and/or metrics used to assess the tool's objectives.
- **Known Entities that Use/Enhance the Tool and Select Research Use Cases:** Examples for how the tool was developed/enhanced through and/or is used in research.
- **Summary:** Summary of key findings from the review of the tool including advantages and gaps/challenges in regard to its usage in research.

Additionally, the summary of this chapter discusses the incorporation of data analytics and AI/ML in AMS for ITS tools developed through and used in research and the applicability of Capability Maturity Models (CMMs) and Technology Readiness Levels (TRLs) to further assess the state of AMS for ITS tools used in research.

Note that the lists of identified tools below are not exhaustive but are instead intended to provide a representative survey/snapshot of AMS for ITS tools developed through and used in research.

Furthermore, there are tools that are included in both the State of Practice report and this State of Research report for AMS for ITS tools due to their broad use in both practice and research. While much of the information is the same for these overlapping tools in the two reports, the highlighted use cases differentiate their applicability in practice and research. Furthermore, the overlapping tools are utilized as they are intended in practice with their preset capabilities. However, in research, these tools may be utilized with their default capabilities to assess new inputs or generate outputs to be further analyzed via other research-developed tools. Additionally, in research, the tools' functionalities/capabilities may be extended or enhanced to address a research problem. These tools are identified by the use of asterisks (*) in both reports.

3.1 Sketch Planning

These tools produce general estimates of travel demand and traffic operations in response to transportation improvements. They use simplified techniques and highly aggregated data, making them the simplest and least costly analysis techniques. However, they are limited in various capabilities including scope, analytical robustness, and presentation [13].

Fidelity and/or Resolution: Sketch planning tools produce general order-of-magnitude estimates and can model transportation/land use demand at the macroscopic or aggregate level.

- Identified tools:
    - EVI-X Suite

3.1.1 EVI-X Suite

3.1.1.1 Tool Description

EVI-X Suite is an integrated set of electric vehicles charging infrastructure analysis tools developed by the National Renewable Energy Laboratory (NREL) used for EV network planning, site design, and financial analysis. The core tool (EVI-Pro) uses travel demand data from travel surveys and EV adoption rates/vehicle models from vehicle registration data to estimate charging station requirements and electric load profiles. Numerous extensions of EVI-Pro have been developed to support additional metrics and use cases (e.g., EVI-Equity, EVI-RoadTrip, EVI-OnDemand). In general, the EVI-X modeling suite informs the development of large-scale EV charging infrastructure deployments from the Regional, State, and National levels to site and facility operations [14]. This suite of tools helps researchers find optimal ways to facilitate a rapid transition to EVs and mitigate the impacts of charging loads on the electric grid. The available tools can be accessed on the NREL's website [14]. To gain access to the tools, prospective users/partners must work with NREL staff except when using EVI-Pro Lite (a simplified, web-based version of EVI-Pro) and EVI-OnDemand (available on GitHub). The EVI-X Suite includes the following tools:

- **EVI-Pro**: Provides charging infrastructure projections based on characteristic daily travel (EVI-Pro Lite is the simplified free version of EVI-Pro for quick estimation) [15], [16].
- **EVI-InMotion**: Enables planning, optimizing, and analyzing the feasibility of charging EVs while driving [17].
- **EVI-EnSite**: Provides charging infrastructure energy estimation and site optimization [17].
- **EVI-Equity**: Conducts equitable distribution of EV charging stations analysis [18].
- **EVI-RoadTrip**: Enables charging infrastructure analysis for long-distance travel [19].
- **EVI-FAST**: Provides charging infrastructure financial analysis [20].
- **EVI-On Demand**: Estimates direct current fast charging (DCFC) infrastructure requirements for ride-hailing vehicle fleets.
- **EVI-Edges**: Estimates behind-the-meter storage optimization to minimize grid impacts from EV charging.

3.1.1.2 Tool Category(ies)

Sketch Planning, Analytical/Deterministic.

3.1.1.3 Primary Purposes/Objectives

EVI-X Suite is intended for performing analysis and modeling of charging infrastructure deployments considering the demand and existing supply of EVs for planning purposes. It provides charging infrastructure projections based on daily travel, dynamic charging infrastructure design, energy estimation and site optimization, equitable distribution of charging stations, and other aspects such as fleet electrification analysis [14].

3.1.1.4 Scope (including applicable ITS component(s))

EVI-X Suite is a sketch planning suite of tools and is not designed for transportation modeling/simulation and respective driving behavior analysis. While ITS strategies are not explicitly modeled by the tools, the output can be utilized for analyzing emissions modeling/monitoring and providing decision support inputs needed for EV demand management.

3.1.1.5 Data Inputs/Requirements

Data required to model and analyze EV charging infrastructure scenarios using the EVI-X Suite include the following:

- Transportation and Land-Use Data (e.g., daily activity/trip pattern data, trip volume and patterns).
- Demographic and Census Data (e.g., household travel surveys, census, choice surveys).
- EV Ownership/Adoption Rate Data.
- Existing Standard and DCFC Charging Stations.

3.1.1.6 Performance Measures/Outputs

Some of the performance measures/outputs generated by EVI-X tools include Energy Delivered Per Charger, Total Energy Delivered (kWh), Battery State of Charge (SOC), Charging Station/Port Utilization, Electric Vehicle Miles Traveled (eVMT), etc.

3.1.1.7 Known Entities that Use/Enhance the Tool and Select Research Use Cases

Table 3. Examples of Known Entities that Use/Enhance EVI-X Suite and Select Research Use Cases

Entity Type	Entity	Use Case	Link
National Laboratory	National Renewable	• Assessment of electric vehicle charging infrastructure in Maryland.	• Zero Emission [21] • Truck electrification [22]

Entity Type	Entity	Use Case	Link
	Energy Laboratory	• Estimate for the impacts of depot charging on electricity distribution systems for heavy-duty truck electrification. • Assessment to understand the charging flexibility of shared automated electric vehicle fleets. • Modeling and analysis of a fast-charging station and evaluation of service quality for electric vehicles.	• Shared Automated Electric Vehicle Fleets [23] • Fast Charging Station Evaluation [24]

3.1.1.8 Summary

Key findings from the review of EVI-X Suite include:

- EVI-X Suite is one of the initial efforts to analyze EV adoption and quantify/estimate the impacts of EV penetration rates on the national grid.
- Its support of planning for equitable distribution of standard or fast charging stations.
- The tool suite has interactive tools that make it easier for analysts to estimate EV impacts.
- Some of the tools within the EVI-X Suite are currently being develop/refined. As of now, EVI-X Suite does not incorporate traffic flow modeling or driver behavior into its analyses.
- EVI-X Suite relies on a network of other transportation data, tools, and capabilities to complete charging infrastructure analysis [14].

3.2 Travel Demand Models

These tools' mathematical models forecast future travel demand based on current conditions and future projections of household, employment, and other traveler characteristics. They have specific analytical capabilities but may have limitations in their abilities to evaluate travel management strategies or accurately estimate changes in operational characteristics resulting from implementation of ITS or operational strategies [13].

Fidelity and/or Resolution: Travel demand tools model transportation systems at the macroscopic level (i.e., low fidelity) and require less detailed representation of the network compared with microscopic and mesoscopic tools.

- Identified tools:
    - TransCAD*
    - Visum*

3.2.1 TransCAD*

This tool is also discussed in the State of Practice Report.

3.2.1.1 Tool Description

TransCAD is a transportation planning software that combines Geographic Information Systems (GIS) and transportation modeling capabilities in a single integrated platform, providing a plethora of capabilities for transportation professionals and researchers. TransCAD can be used for all modes of transportation, at any scale or level of detail. TransCAD provides a GIS engine with special extensions for transportation mapping, visualization, and analysis tools designed for transportation applications; and application modules for vehicle and routing logistics, travel demand forecasting, public transit, site location, and territory management analyses [25], [26]. Newer functionalities and capabilities include activity-based modeling, freight applications (first and last mile), transit accessibility measures as well as statistical and machine learning models for predictions such as regression modeling, classification decision trees for trip generation/population synthesis, and discrete choice modeling [27], [28]. Developed by the Caliper Corporation, TransCAD can perform the four-step forecasting process or activity- and tour-based modeling, either manually using built-in menus or by using custom coding in the GIS Developer's Kit (GISDK) interface. In the four-step forecasting process, TransCAD provides alternative methodologies for each step of the transportation forecasting process such as cross-classification techniques (for trip generations), equilibrium, all-or-nothing, incremental, system optimal (for traffic assignment). TransCAD also includes most of the current U.S. census data for varying spatial levels and provides tools for accessing and viewing this data. Moreover, routing functionality allows the tool to perform logistics analyses and system planning [29]. TransCAD is a commercial tool and requires a paid license to obtain access. There is also an academic version of license with options for single workstation use or for laboratory research work [25].

3.2.1.2 Tool Category(ies)

Travel Demand Models, Sketch Planning.

3.2.1.3 Primary Purposes/Objectives

TransCAD is a transportation planning tool that supports methods for forecasting and modeling travel demand of a given area and assigning it to a road network. The tool supports all modes of travel and has capabilities to model public transit, non-motorized travel (i.e., pedestrians and bicyclists) and freight applications [30]. The tool is used by many academic institutions to supplement the coursework in transportation planning/modeling [31]. The tool is used for several research purposes including but not limited to transportation network analysis, public transit accessibility measurement, choice modeling (discrete choice, mode choice, route choice), user equilibrium analysis, dynamic traffic assignment (DTA), and non-motorized travel analysis [27].

3.2.1.4 Scope (including applicable ITS component(s))

TransCAD can model cities, regions, and country-wide travel demand. TransCAD supports few ITS applications such as emissions modeling [32], toll lanes [27], and dynamic traffic routing (TransDNA) [33]. However, TransCAD can be integrated with another Caliper product, TransModeler, that is a microscopic tool to model and assess the macro-level impacts of additional ITS applications such as ramp metering, transit signal priority, variable speed limits, hard shoulder running, and high occupancy toll (HOT) lanes.

3.2.1.5 Data Inputs/Requirements

The TransCAD subscription/license includes geographic and demographic data such as U.S. boundary files with census demographic data, U.S. streets and highways, landmarks, and Metropolitan Statistical Areas (MSAs), etc. [34]

Data required to conduct travel demand modeling and analysis using TransCAD include the following:

- Geometric Data: GIS-based network data including traffic analysis zones, jurisdiction boundaries, street centerlines, transportation network links and nodes, etc.
- Forecasts of future population, households, and employment throughout the analysis zones.
- Information about future transportation networks: changes that are planned, or potential changes to be tested that are anticipated to improve the current transportation system.

3.2.1.6 Performance Measures/Outputs

Some of the performance measures/outputs generated by TransCAD include Average Traffic Volume, Vehicle Miles Traveled (VMT) by traveler type, Average Travel Times, Average Speeds, Transit Ridership, Transit Level of Service (LOS), Transit Accessibility Measures (access, egress, walk, and transfers to transit), Emissions Per Mile, Total Trips, Total Miles, etc. [27], [32]

3.2.1.7 Known Entities that Use/Enhance the Tool and Select Research Use Cases

Table 4. Examples of Known Entities that Use/Enhance TransCAD and Select Research Use Cases

Entity Type	Entity	Use Case	Link
Academic Institution	University of Texas at Austin	• Incorporation of AVs in the Traditional Four-Step Model. • Assessment of anticipated regional impacts of CAV travel in Austin, TX.	• AVs [35] • CAVs [36]

Entity Type	Entity	Use Case	Link
National Laboratory	Oak Ridge National Laboratory	• Model for inclusion of innovative scenarios for intra-city freight delivery. • Proposed methodology for a tour-based freight model.	• Intra-City Freight Delivery [37] • Tour-based Freight Model [38]
Academic Institution	Hanyang University, Seoul, South Korea	Model to assess benefits of travel time savings by truck platooning in Korean freeway networks.	Truck platooning [39]

3.2.1.8 Summary

Key findings from the review of TransCAD include:

- The tool consists of a single platform that is able to perform multiple functions, including model application, model estimation, database support, GIS-based analysis, and graphical/analytical postprocessing, etc.
- Its capability to support all major methodologies of travel demand modeling methods, including sketch planning methods, four-step demand models, activity-based demand models, and other advanced disaggregate modeling techniques.
- Its support of various modeling options (e.g., discrete choice models, mode choice models) [28].
- Its ability to perform integrated modeling of all modes of transportation including car, HOV, truck, bus, rail, bicycle, and pedestrian movements.
- Its incorporation of visualizations with dozens of thematic mapping styles and options.
- TransCAD has U.S. geographic and census demographic data embedded in the tool.
- Its ability to be integrated with TransModeler to create a multiresolution model for more comprehensive modeling.
- Its incorporation of ML algorithms, such as decision trees, that are explainable for population synthesis [28].
- Access to TransCAD requires a paid license.
- Additional skills and training may be needed to make full use of the tool's functionalities. For example, knowledge on GISDK scripting may be required to incorporate custom scenarios such as AV demand modeling [36].

3.2.2 Visum*

This tool is also discussed in the State of Practice report.

3.2.2.1 Tool Description

Visum is a simulation software tool used for transportation planning, travel demand modelling, and network data management. Designed for multimodal analysis, Visum integrates a variety of modes of transportation (i.e., passenger cars, trucks, buses, trains, motorcycles, bicycles, and pedestrians) into one consistent network model. Visum provides a variety of dynamic assignment procedures and four-step modelling components, which include trip-based as well as activity-based approaches. This tool's demand modelling at the macroscopic level (or mesoscopic level with simulation-based assignment) can be integrated with microscopic traffic and pedestrian simulation (Vissim) to provide transportation professionals and researchers with suites of analysis tools for transportation planning. Additionally, the tool's graphical user interface (GUI), scripting, and application programming interface (API) allow researchers to expand on Visum's standard functionalities to incorporate more advanced applications. Visum is developed by the PTV Group and requires paid license to obtain access [40], [41].

3.2.2.2 Tool Category(ies)

Travel Demand Models, Macroscopic Simulation, Mesoscopic Simulation.

3.2.2.3 Primary Purposes/Objectives

Visum is primarily used to assist transportation agencies and researchers plan for future investments in transportation infrastructure and sustainable mobility. This is achieved by performing multimodal simulation of the transportation system and forecasting/assessing demand for various scenarios [41]. Results from Visum traffic simulations are intended to help users understand which operational and infrastructure enhancements yield the best performance.

3.2.2.4 Scope (including applicable ITS component(s))

Visum is a travel demand and macroscopic simulation tool that models transportation networks at the city and regional levels. Since ITS applications are often implemented at the microscopic and mesoscopic models, Visum may not directly model ITS applications. However, when integrated with microscopic tools such as Vissim, impacts of ITS applications can be assessed at the macroscopic level.

Data Inputs/Requirements

Data required to model and conduct simulation using Visum include the following:

- Geometric Data: GIS-based network data including traffic analysis zones, jurisdiction boundaries, street centerlines, transportation network links and nodes, etc.
- Traffic Flow/Travel Demand Data: Origin-Destination (O-D) matrix for different vehicle types, average travel times and speeds, public transit routes and stops, etc.

- If integrated with other tools such as a microscopic simulation tools, additional data such as signal timing data will be needed.

3.2.2.5 Performance Measures/Outputs

Some of the performance measures/outputs generated by Visum include Average Travel Times, Average Speeds, Delay, Density, VMT, etc.

3.2.2.6 Known Entities that Use/Enhance the Tool and Select Research Use Cases

Table 5. Examples of Known Entities that Use/Enhance Visum and Select Research Use Cases

Entity Type	Entity	Use Case	Link
Academic Institution	University of Southern California	Model to evaluate a load balancing mixed freight coordinated assignment system with the inclusion of diesel and electric trucks on realistic road networks aiming for the optimal total combined cost of energy consumption and time.	Dynamic Routing of Trucks and Truck Platoons Using Real-Time Traffic Simulators. [42]
Academic Institution	Florida Atlantic University	Integrated Visum and Vissim model to evaluate the impacts of complete streets.	Multiresolution Analysis of the Impacts of Complete Streets on Efficiency, Safety and Environment of Urban Corridors. [43]
Academic Institution	Warsaw University of Technology	Model to simulate bicycle traffic in Warsaw, Poland.	Modeling Bicycle Traffic Using Visum [44]

3.2.2.7 Summary

Key findings from the review of Visum include [41]:

- Its inclusion of a GUI that is easy to use and enables efficient design of network scenarios.
- Its support of activity-based demand models, which model mobility decisions of individuals instead of groups, in addition to four-step trip-based demand modeling.
- Its incorporation of all standard modes of transportation – drive-alone auto, carpool, public transit, bicycles, pedestrians, and trucks.

- Its ability to integrate with Vissim for more comprehensive multiresolution modeling and simulation.
- Additional skills/training may be needed to effectively use the tool.
- Access to this tool requires a paid license.

3.3 Analytical/Deterministic

Analytical or deterministic tools operate under the assumption that there is uniformity in driver-vehicle characteristics. Typically, these tools follow the procedures outlined in the Highway Capacity Manual (HCM), where a practitioner inputs data and parameters, and the HCM procedures generate a single output after a series of analytical steps. This enables the tools to rapidly predict performance metrics such as capacity, density, speed, delay, and queuing for a range of transportation facilities. The accuracy of these tools is validated through field data, laboratory testing, or small-scale experiments. Analytical or deterministic tools are particularly useful for evaluating the performance of small or isolated transportation facilities [13]. A few are presented in this report to highlight the specific capabilities in terms of complexity, and level of usage by transportation practitioners.

- Identified tools: No AMS tools were identified in the with Analytical/Deterministic as their principal category during the literature review that were both identified as currently part of the state of research and included at least one ITS component. There are several tools from [13] that fall within this category, but these are either not identified as part of well-known research within the past three to five years/are outdated or do not readily include ITS components.

3.4 Traffic Optimization

These tools develop optimal signal phasing and timing plans for isolated signal intersections, arterial streets, or signal networks based on HCM procedures. Advanced tools can model actuated and semi-actuated traffic signals, with or without signal coordination [13].

- Identified tools: No AMS tools were identified with Traffic Optimization as their principal category during the literature review that were both identified as currently part of the state of research and included at least on ITS component. There are several tools from [3] that fall within this category, but these are either not identified as part of well-known research within the past three to five years/are outdated or do not readily include ITS components.

3.5 Macroscopic Simulation

These tools simulate traffic flow based on deterministic relationships of flow, speed, and density, focusing on aggregate speed/volume and demand/capacity relationships. They have fewer computational demand requirements than microscopic simulation tools, but they do not provide as much detail in analyzing transportation improvements [13].

- Identified tools: No AMS tools were identified with macroscopic simulation as their principal category during the literature review that were both identified as currently part of the state of research and included at least one ITS component. There are several tools from [13] that fall within this category, but these are either not identified as part of well-known research within the past three to five years/are outdated or do not readily include ITS components.

3.6 Mesoscopic Simulation

Mesoscopic models describe traffic facilities at a higher level of resolution compared with macroscopic models, but the behavior and interactions of vehicles exhibit a lower level of fidelity compared with microscopic models. Mesoscopic simulation models aim to fill the gaps between the aggregate-level approach of macroscopic models and the individual interactions of microscopic models [45]. Compared with microscopic models, mesoscopic models can provide significant savings in modeling time and efforts, especially when analyzing large area networks, without unduly compromising the accuracy of results [46]. Outputs from mesoscopic models include time-varying traffic flow dynamics and traveler path choice behavior. There are many commercial and open-source mesoscopic simulation tools at the disposal of transportation practitioners and researchers. However, several are presented in this report to highlight the different types in terms of methodology, complexity, and recent uses/developments by transportation researchers.

Fidelity and/or Resolution: Mesoscopic simulation tools model transportation systems at the mesoscopic level. As a result, the level of detail and fidelity of network representation are less compared to those for microscopic models but higher than those for macroscopic models.

- Identified tools:
  - MATSim
  - BEAM CORE
  - DynaMIT
  - DTALite
  - POLARIS

3.6.1 MATSim

3.6.1.1 Tool Description

Multi-Agent Transport Simulation (MATSim) is an open-source platform used for executing large scale agent-based transportation simulations. The simulation process begins by assigning tours (based on the area population's daily activity patterns) to agents using empirical data and discrete choice models. The network is then simulated at the microscopic level using a queue-based approach to reduce computation times. The replanning phase is then initiated for agents to make alternative plans based on utility maximization. This process (network simulation and replanning) is repeated until population utility stabilizes. The MATSim framework is comprised of various modules that can either be combined or utilized independently. MATSim offers capabilities including modeling demand, simulating agent-based mobility (i.e., traffic flow), and re-planning (i.e., revision of agents' plans), implementing an iterative control mechanism for running simulations, and methods for analyzing the results produced by its various modules. This tool is maintained and updated by the MATSim Community, consisting of academic and research institutions, and the recently created more formal MATSim Association. [47]

3.6.1.2 Tool Category(ies)

Mesoscopic Simulation, Microscopic Simulation, Travel Demand Models.

3.6.1.3 Primary Purposes/Objectives

MATSim is used to simulate primarily large-scale transportation networks, including road networks, public transit systems, and pedestrian and cycling infrastructure. It is also used to model the travel behavior of individual travelers, considering their preferences, constraints, and decision-making processes. Additionally, MATSim can be used to optimize traffic flow by modeling the interactions of individual travelers with the transportation network, and adjusting traffic signals, routes, and other factors to improve overall traffic flow. Further, MATSim can be used to evaluate transportation policies and infrastructure improvements by simulating the impacts of these changes on travel behavior and traffic flow. MATSim can also support transportation planning and operations by providing insights into the likely outcomes of different transportation scenarios and identifying potential challenges and opportunities, such as for evacuation planning [48], [49].

3.6.1.4 Scope (including applicable ITS component(s))

MATSim is used for link- and network-wide (comprising of local roads, arterials, and freeways) analysis. MATSim can model various types of traffic signals, including fixed-time signals, actuated signals, and adaptive signals. It can also simulate different types of traffic management strategies, including ITS strategies such as ramp metering and dynamic traffic assignment. Furthermore, MATSim can model/simulate various types of ITS technologies, such as Advanced Traveler Information Systems (ATIS) and AVs [48], [50].

3.6.1.5 Data Inputs/Requirements

Data required to model and conduct simulation using MATSim include the following:

- Network Data: Locations and properties (such as such as roads, bus stops, and train stations) of all transportation infrastructure, typically provided in a network file format, such as the OpenStreetMap (OSM) format [48].
- Population Data: List of agents, where each agent possesses a memory of a list of plans that is composed of daily activity chains for the agent and legs. A leg describes how the agent plans to travel from one location to another and has attributes associated with it, such

as mode, expected travel time, and route choice. This data is typically provided in a population file format, which includes information about the travel preferences and behavior of each individual traveler [48].

- Travel Demand Data: Agents and their plans, including activity types, activity durations, activity locations, trip modes, and trip routes [51].
- Public Transport Data (if simulation includes public transport): Locations of public transport facilities, lines and their routes, vehicle capacities, and arrival/departure times at stops along the routes [51].

3.6.1.6 Performance Measures/Outputs

MATSim can generate a wide range of performance measures/outputs related to transportation system performance and traveler behavior such as Travel Time, Travel Delay, Speed, Queue Lengths, Capacity Utilization, Network Accessibility (measure of the ease with which a section/portion of a network can be accessed), Emissions, Energy Consumption, Noise Pollution, etc. [48]

3.6.1.7 Known Entities that Use/Enhance the Tool and Select Research Use Cases

Table 6. Examples of Known Entities that Use/Enhance MATSim and Select Research Use Cases

Entity Type	Entity	Use Case	Link
Academic Institutions	University of Alabama; Louisiana State University	Model to estimate the potential benefits of increased public transit ridership in medium sized cities.	Public Transit Operations [52]
Academic Institution	Virginia Tech	Agent-based simulation model to evaluate merits of connected corridors and determine future steps.	Agent-based Modeling [53]
Research Institutions	Institute for Transport Planning and Systems; IRT SystemX	Model to simulate intermodal shared mobility in the San Francisco Bay Area, CA.	Shared Mobility [54]

3.6.1.8 Summary

Key findings from the review of MATSim include:

- MATSim is an agent-based modeling framework. So rather than just aggregating travelers into groups or averaging their behaviors, this tool allows for a more detailed understanding of the transportation system and the ability to capture complex behaviors and interactions between agents [48].
- It is an open-source framework that is available, customizable, and adaptable to a wide range of transportation systems and research questions [48].
- It has the ability to simulate large-scale transportation systems with thousands to millions of agents with its scalability. This enables modeling of urban transportation systems and evaluating the impacts of transportation policies and interventions [47].
- It has the ability to generate realistic activity schedules for agents, considering factors such as time constraints, mode availability, and activity location, which allows for more accurate modeling of transportation demand that can help identify areas where transportation infrastructure and services may be lacking [48].
- MATSim requires significant computational resources and time to run simulations for a large-scale transportation system and/or a large number of agents with detailed activity plans [55].
- Users of the tool may experience challenges with ensuring accurate calibration and validation when trying to match the simulation results to real-world data, which can lead to uncertainty in the results and limit the usefulness of the simulation for decision-making [56].
- Accuracy of the tool's outputs is highly dependent on the quality and availability of data, which may not be available or may be prohibitively expensive to obtain [56].
- The tool has a highly complex modeling framework that can be difficult for non-transportation modeling experts to use and understand, which can be a barrier to adoption [57].
- Additional skills and training may be required to make full use of the tool's functionalities.
- As an open-source tool, there is limited technical support available to users.

3.6.2 BEAM CORE

3.6.2.1 Tool Description

Behavior, Energy, Autonomy, and Mobility Comprehensive Regional Evaluator (BEAM CORE) is an open-source [58] long-range mesoscopic simulation planning tool developed by Lawrence Berkeley National Laboratory (LBNL) and funded by U.S. Department of Energy (DOE) [59]. BEAM CORE is an extension of the previously developed BEAM model, which is an activity- and agent-based regional transportation mesoscopic simulation modeling tool that leverages the MATSim framework (utility maximization, queue-based microsimulation, etc.). The CORE enhancements of BEAM (compared to MATSim) include improved computational time through parallelization and transitioning from fixed-increment time advance modeling to event-based modeling, improved mode choice options, incorporation of ride-hailing options, dynamic within-day planning, and the consideration of resource markets. In aggregate, BEAM CORE facilitates a scalable simulation of regional transportation systems and provides transportation planners, service providers, and researchers with the ability to simulate the behavior of travelers and the deployment of technology to comprehend the implications of novel mobility technologies and services on congestion, energy, and emissions, ranging from individual level to the entirety of transportation systems. [60]

3.6.2.2 Tool Category(ies)

Mesoscopic Simulation.

3.6.2.3 Primary Purposes/Objectives

BEAM CORE is used by academic institutions and national laboratories to evaluate the impacts various operational and control strategies as well as emerging technologies are anticipated to impact travelers and the transportation network ahead of deployments. It is also used to understand how results from a limited pilot programs will scale to a broader implementation [60].

3.6.2.4 Scope (including applicable ITS component(s))

BEAM CORE is capable of modeling transportation systems at a regional scale including transit (bus and rail) system design, land-use development, and freight demand operations. It is also capable of modeling ITS applications and emerging technologies including AVs, EVs and emissions monitoring, low emissions zone management, dynamic lane management, shared mobility (e.g., ride-hailing, shared scooters, e-bikes, and micro-transit), telecommuting, freight last-mile delivery innovations, and congestion pricing, etc.

3.6.2.5 Data Inputs/Requirements

Data required to model and conduct simulation using BEAM CORE are similar to that of MATSim and include the following [59]:

- Network Data: Locations and properties (such as roads, bus stops, and train stations) of all transportation infrastructure. Note that traffic signal and control is not represented in the network.
- Population Data: Demographic and census data for population synthesis (demand represented by agents and their daily activity/trip plans).
- Public Transport Data (if simulation includes public transport): Transit schedules, routes, facilities data, etc.
- Survey Data: Stated preference choice for newer forms of mobility such as transportation network companies (TNC) usage, EV ownership, emerging technology adoption, etc.

3.6.2.6 Performance Measures/Outputs

Some of the performance measures/outputs generated by BEAM CORE include Greenhouse Gas (GHG) Emissions, Energy Consumption Per Mile, VMT, Passenger-Miles Traveled (PMT), Vehicle Hours Traveled (VHT), Ratio of VMT/VHT, Vehicle Occupancy (both public and private transportation), Freight-Specific Measures, etc. [59]

3.6.2.7 Known Entities that Use/Enhance the Tool and Select Research Use Cases

Table 7. Examples of Known Entities that Use/Enhance BEAM CORE and Select Research Use Cases

Entity Type	Entity	Use Case	Link
Academic Institution	San Jose State University	Simulation of the introduction of on-demand, automated, and electric shuttles for last mile connectivity in Santa Clara County, CA.	On-Demand, Automated, and Electric Shuttles [61]
National Laboratory	NREL	Models to help plan for and inform about smart cities.	Smart Cities [62]
National Laboratory	LBNL	Model to understand plug-in electric vehicle charging demand and develop a framework for behavior energy autonomy mobility.	Modeling EVs [63]

3.6.2.8 Summary

Key findings from the review of BEAM CORE include [59], [64]:

- Its ability to simulate large scale networks.
- Its ability to model newer forms of transportation such as ride-hailing, micro-mobility, electric vehicles, etc.
- BEAM CORE utilizes publicly available data (e.g., OSM, General Transit Feed Specification [GTFS], etc.).
- The tool requires significant computational power and resources.
- BEACK CORE lacks a graphical interface and requires prior programming experience, which can hinder accessibility.
- Users of the tool require the tool developers' support to understand the latest capabilities and functionalities, which are constantly updated. However, since BEAM CORE is an open-source tool, there may be limited technical support available to users.
- Output files require post-processing.
- Additional skills and training may be required to make full use of the tool's functionalities.

3.6.3 DynaMIT

3.6.3.1 Tool Description

Dynamic Network Assignment for the Management of Information to Travelers (DynaMIT) is a real-time dynamic traffic assignment system that utilizes both offline and real-time information to provide traffic predictions and travel guidance. The offline information includes the network description and historical data, and real-time information is provided by the surveillance and control systems. DynaMIT is composed of two components: 1) demand simulator, and 2) mesoscopic traffic simulator. The demand simulator estimates/predicts O-D time dependent travel times, which are then input into discrete choice models to determine route choice, mode choice, and departure time at the disaggregated level. Demand between origins and destinations are modeled at the aggregate level. The mesoscopic traffic simulator is used to model traffic behavior based on estimated O-D demand. The simulator first updates network conditions and then advances traffic entities to their new positions. Link level speeds are based on macroscopic speed-density relationships and the evolution and dissipation of queues are modeled using deterministic queueing methods [65]. DynaMIT is a commercial tool developed by researchers at the Massachusetts Institute for Technology. The tool is compatible with a variety of surveillance and control systems [66], [67], [68]. DynaMIT takes real-time data from sensors and estimates the current state of the transportation network. Based on this information, it then predicts the immediate future condition of the transportation network and provides this information to travelers for guidance [69].

3.6.3.2 Tool Category(ies)

Mesoscopic Simulation, Multiresolution Hybrid Meso-Micro Simulation [70].

3.6.3.3 Primary Purposes/Objectives

DynaMIT is a mesoscopic tool tools used to support the operation of ATIS and Advanced Traffic Management Systems (ATMS) at Traffic Management Centers (TMC) by optimizing their operations through the provision of real-time predictions [70].

3.6.3.4 Scope (including applicable ITS component(s))

DynaMIT models links and networks at the mesoscopic level. DynaMIT can be used to generate historical databases and model coordination efforts for evacuation and rescue operations in real-time emergencies (e.g., natural disasters, etc.). This tool can also model, simulate, and evaluate ITS technologies such as Variable Message Signs (VMS) as well as ITS strategies including alternative traffic signal control schemes, ramp metering, and real-time incident management and control [70].

3.6.3.5 Data Inputs/Requirements

Data required to model and conduct simulation using DynaMIT include the following [66], [71].

- Travel Demand Data: Time-dependent O-D matrices.
- Real-Time Traffic Flow and Other Exogenous Data: Real-time traffic counts from the surveillance systems, incident reports, weather information, speed, flow, trajectory data.
- Geometric Data: Links, nodes, and loading elements. Links represent unidirectional pathways between the nodes. Nodes correspond to intersections of the actual network. The loading elements represent locations where traffic is generated or attracted.
- Traffic Control Data: Toll gates, ramp meters, etc.

3.6.3.6 Performance Measures/Outputs

Some of the performance measures/outputs generated by DynaMIT include Travel Time (mins), Flows (veh/hr), Densities (veh/ln/mi), Queue Length (ft), etc. [72]

3.6.3.7 Known Entities that Use/Enhance the Tool and Select Research Use Cases

Table 8. Examples of Known Entities that Use/Enhance DynaMIT and Select Research Use Cases

Entity Type	Entity	Use Case	Link
Academic Institution	Massachusetts Institute of Technology (MIT); Delft University of Technology	Model for dynamic toll pricing using dynamic traffic assignment system with online calibration.	Toll Pricing [73]
Academic Institution	University of Massachusetts	Optimization of transportation systems using an information provision, personalized incentives, and driver cooperation.	Transport Systems Optimization [74]
Academic and Research Institutions	MIT; Singapore-MIT Alliance for Research and Technology; Technical University of Denmark (DTU); National Technical	Real-time data fusion for traffic prediction and crisis management architecture.	Real-Time Data Fusion [71]

Entity Type	Entity	Use Case	Link
	University of Athens		

3.6.3.8 Summary

Key findings from the review of DynaMIT include [70]:

- It is able to handle a variety of real-time scenarios such as for incidents, special events, adverse weather conditions, highway construction activities, fluctuations in demand, etc.
- It is able to distinguish between informed and uninformed drivers.
- DynaMIT has long simulation run times.
- It is unable to simulate traffic for large scale networks.
- DynaMIT requires a paid license to access the tool.
- Additional skills and training may be required to make full use of tool's capabilities.

3.6.4 DTALite

3.6.4.1 Tool Description

DTALite is an open-source computationally efficient dynamic traffic assignment mesoscopic simulation modeling tool developed to allow rapid utilization of agent-based dynamic traffic analysis capabilities. DTALite utilizes a queue-based model that uses point queue, spatial queue, and Newell's Simplified Kinematic Wave Theory to estimate dynamic flows and travel times based on O-D demand [75]. DTALite has a visualization component and GUI called Network eXplorer for Traffic Analysis (NeXTA). The tool's four major modeling components include: 1) time-dependent shortest path finding module, 2) vehicle/agent attribute generation module combining an O-D demand matrix with a time of the day departure time profile to generate trips, 3) dynamic path assignment module considering factors affecting agents' route/departure time choice, and 4) queue-based traffic flow module that can incorporate road capacity reducing or increasing events, operations, and/or control strategies such as work zones, incidents, and ramp meters [75]. DTALite allows transportation practitioners and researchers to test various ITS and traffic management strategies. The tool's user guide and source code can be accessed on its GitHub site: [76].

3.6.4.2 Tool Category(ies)

Mesoscopic Simulation.

3.6.4.3 Primary Purposes/Objectives

The primary objective of a DTALite model is to capture the dynamic decision making (route and departure time choice) of individual travelers given various factors, including congestion and traffic incidents. DTALite is used to test various traffic management and ITS strategies [75], [77]. DTALite is also used for analyzing formation, propagation, and dissipation of traffic congestion on a transportation network. The tool has the capability to self-calibrate by iteratively adjusting path flow volume and distribution to match observed traffic counts [75].

3.6.4.4 Scope (including applicable ITS component(s))

The tool can evaluate various ITS at the path, link, or network level, including signal optimization, ramp metering, dynamic pricing, eco-routing, smart work zones, etc., and traffic management strategies and make recommendations for optimal solutions based on the anticipated impacts.

3.6.4.5 Data Inputs/Requirements

Data required to model and conduct simulation using DTALite include the following:

- Network Data: Represented as a link-node diagram.
- Travel Demand Data: Represented as O-D matrices.
- ATMS Strategies: Such as congestion mitigation, signal optimization, ramp metering, road pricing, green routing, pre-trip and enroute information, etc.
- Emissions Data: From the Motor Vehicle Emissions Simulator (MOVES) or other sources is required when modeling emissions.

3.6.4.6 Performance Measures/Outputs

Some of the performance measures/outputs generated by DTALite include Time Dependent Link-, Path-, and Network-Level Travel Times, Speed, Density, Volumes, Vehicle Distributions, Vehicle Trajectories, Vehicle Speed/Acceleration Profiles, Fuel Consumption, Emissions, etc.

3.6.4.7 Known Entities that Use/Enhance the Tool and Select Research Use Cases

Table 9. Examples of Known Entities that Use/Enhance DTALite and Select Research Use Cases

Entity Type	Entity	Use Case	Link
Academic Institutions	University of Maryland; Arizona State University	Model for an integrated and personalized traveler information	Integrated Activity-Based

Entity Type	Entity	Use Case	Link
		and incentive scheme for energy efficient mobility systems.	Model (ABM) and DTA [78]
Academic Institutions	National Chiao Tung University; Arizona State University; Beijing Jiaotong University; Purdue University; North Carolina State University	Model for eco-system optimal time-dependent flow assignment in a congested network.	Optimal Eco-Routing [79]
Academic Institution	Kostychev Ryazan State Agrotechnological University	Model of a decision support system for transport corridors based on dynamic transport flow distribution.	Decision Support System (DSS) for Ryazan City [80]

3.6.4.8 Summary

Key findings from the review of DTALite include:

- It is able to model the dynamic nature of transportation networks [75], optimal eco-routing/green routing flows that minimize vehicular emissions in a congested network [79], and optimized ITS and traffic management strategies [75], [79].
- It is interoperable with inputs/outputs to/from other tools such as MOVES (emissions model), agent-based models, etc. [77], [78]
- Additional skills and training may be required to make full use of the tool's functionalities.
- As an open-source tool, there is limited technical support available to users.
- DTALite uses a simplified model to represent signalized intersections (i.e., the traffic signal cycle's effective green times) and does not include all parameters (e.g., offset, coordination, etc.) [75].
- The tool has difficulty representing complex traffic control intersections.
- DTALite can only represent vehicular traffic and no other modes of transportation.

3.6.5 POLARIS

3.6.5.1 Tool Description

POLARIS is an activity- and agent-based mesoscopic transportation simulation tool developed by Argonne National Laboratory for the FHWA to analyze transportation system management strategies involving emerging vehicle and information technologies [81]. This tool has three components: 1) an individual traveler's route choice model in response to traffic information, 2) a route generation model using travel costs, and 3) a mesoscopic traffic simulation model. The route choice model is based on a bounding rationality enroute switching model to realistically capture enroute behavior based on real-time information. The route generation model calculates least time routes through a routing agent that uses heterogenous sources of traffic information. The traffic simulation model uses Newell's Simplified Kinematic Wave Theory traffic flow model, which has been shown to be effective for large-scale networks and dynamic traffic assignment formulations. While POLARIS is an open-source package, a license request must be submitted through the tool's website [81].

3.6.5.2 Tool Category(ies)

Mesoscopic Simulation.

3.6.5.3 Primary Purposes/Objectives

POLARIS is used for policy, planning and operation, and research purposes. At the planning level, POLARIS is used to model the impacts of CAVs, MaaS, EVs and charging infrastructure, freight logistics, as well as system optimization. At the operational level, POLARIS is used to test various ITS and traffic management strategies. Other purposes include activity generation, activity planning (i.e., choice modeling), and multimodal transportation analysis.

3.6.5.4 Scope (including applicable ITS component(s))

POLARIS is used for large-scale (city or regional level) and summarizes statistics by link and nodes. The tool is also capable of modeling several ITS strategies, including emissions modeling, dynamic traffic management and intersection control, dynamic lane management, and variable speed control [82].

3.6.5.5 Data Inputs/Requirements

Data required to model and conduct simulation using POLARIS include the following:

- Travel Surveys (e.g., TNC usage, bike share, transit preference).
- Census and Employment Data.
- Transportation Network Geometry (e.g., links, nodes, facilities).
- Transit Data (e.g., routes, schedules, stops).
- Vehicle Ownership and Registration.
- Land Use Data.

3.6.5.6 Performance Measures/Outputs

Some of the performance measures/outputs generated by POLARIS include Average Speed, Density, Flow Rate, Energy Consumption, Travel Time, VMT, etc. [82]

3.6.5.7 Known Entities that Use/Enhance the Tool and Select Research Use Cases

Table 10. Examples of Known Entities that Use/Enhance POLARIS and Select Research Use Cases

Entity Type	Entity	Use Case	Link
National Laboratories, Academic Institutions	Argonne National Laboratory; University of Illinois at Chicago; Illinois Institute of Technology; University of Chicago; George Mason University; Michigan Technological University	Simulation model for coordinated transit response planning and operations support for mitigating impacts of hazard emergency events.	Emergency Transit Response [83]
National Laboratory	Argonne National Laboratory	Simulation model to evaluate the transportation energy impact of future population scenarios for Detroit, MI.	Energy Impact [84]
National Laboratory	Argonne National Laboratory	Simulation model to assess travel demand and energy impacts of privately-owned level 4 CAV technologies.	Impact of Level 4 CAV [85]

3.6.5.8 Summary

Key findings from the review of POLARIS include [81], [82]:

- It is able to model multimodal metropolitan transportation systems, ITS, and traffic management strategies.
- The tool is able test the impact of emerging mobility and technologies.
- POLARIS is able to simulate 10 million agents (i.e., vehicles) in 4-6 hours of model run time.
- Some of the data coming from stated preference (SP) choice surveys may vary based on geographical location.
- It is not easily integrable with existing modeling tools due to its use of an agent-based approach, while other tools use approaches such as trip/tour-based approaches, four step modeling, etc. [86]
- A license must first be obtained to use this open-source tool.

3.7 Microscopic Simulation

These tools simulate the movement of individual vehicles based on car-following and lane-changing theories, with each vehicle assigned a destination, vehicle type, and driver type. They require significant computational time and storage, which may limit the network size and the number of simulation runs that can be completed in a given timeframe [13]. In microscopic simulation tools, extensive coding efforts is required to build a traffic network compared with mesoscopic and macroscopic simulation tools.

Fidelity and/or Resolution: Microscopic simulation tools are high-fidelity traffic simulation tools that model interactions between individual vehicles (and other transportation infrastructure users) and represent the transportation network with greater level of detail, leading to higher resolution and higher fidelity.

- Identified tools:
  - CARLA
  - Vissim*
  - CORSIM*
  - TransModeler*
  - Paramics*
  - MITSIMLab
  - INTEGRATION
  - SUMO*
  - Aimsun*
  - Unity 3D

3.7.1 CARLA

3.7.1.1 Tool Description

CAR Learning to Act (CARLA) is an open-source microscopic simulation platform designed to support research on automated driving systems (ADS). CARLA was specifically developed to facilitate the creation, training, and validation of ADS in urban environments. Along with providing open-source code and protocols, CARLA offers freely available digital assets such as urban layouts, buildings, and vehicles. The simulator platform allows for flexible customization of sensor suites and environmental conditions [87]. CARLA utilizes the Unreal Engine for simulation and adopts the OpenDRIVE standard to define roads and urban settings. The simulation is controlled through a Python and C++ based API. CARLA's architecture is based on a scalable client-server model. The server component handles the simulation itself, including sensor rendering, computational physics, and updates on the world-state and its actors. On the client side, various modules control the behavior of actors in the scenes and establish world conditions. This functionality is achieved by utilizing the CARLA API, which serves as a mediator between the server and the client. The CARLA API is continually evolving to offer new functionalities. For example, research efforts have used data-driven end-to-end (E2E) deep learning ML with CARLA to train vehicles to adhere to road guidelines and remain within a specific lane, navigate through urban environments while avoiding obstacles, and develop strategies for longitudinal motion control, among other efforts [88].

3.7.1.2 Tool Category(ies)

Microscopic Simulation.

3.7.1.3 Primary Purposes/Objectives

The main purpose of CARLA is to facilitate the training, prototyping, and validation of various approaches to automated driving, encompassing both perception and control aspects, specifically the perception algorithms or learning driving policies. It provides a means to test various automated driving policies under varying environmental and operational conditions [89].

3.7.1.4 Scope (including applicable ITS component(s))

CARLA supports the modeling and simulation of how automated vehicles interact with each other, pedestrians, and transportation infrastructure (e.g., traffic controls such as signals, signs, markings, etc.). It can model scenarios on surface streets, freeways, and within the general urban driving environment. CARLA can model passenger vehicles as well as buses/shuttles. This tool is used to model and simulate the emerging ITS technologies of AVs and cooperative automated driving (e.g., ramp metering). It can be integrated with other microscopic simulation tools to model ITS strategies and examine how autonomous vehicles respond to such strategies.

3.7.1.5 Data Inputs/Requirements

Data required to model and conduct simulation using CARLA include the following:

- Autonomous Vehicle Data: Vehicle type, color, type of control, vehicle lights on/off, etc. selected from the Blueprint Library in CARLA.
- Traffic Control Data: Traffic signs and traffic lights.
- Roadway Geometry Data: Number of lanes, junctions, lane widths, etc.
- Pedestrian Data: Age, gender, walking speed, etc. selected from the Blueprint Library in CARLA.
- Weather Data: Type of prevailing weather/lighting conditions such as rain, clear day, clear sunset, daytime shortly after rain, etc.

3.7.1.6 Performance Measures/Outputs

Some of the performance measures/measures generated by CARLA include Percentage of Success, Average Completion, Off Road Intersection, Other Lane Intersection, Vehicle Collisions, Pedestrian Collisions, General Collisions, etc. [90]

3.7.1.7 Known Entities that Use/Enhance the Tool and Select Research Use Cases

Table 11. Examples of Known Entities that Use/Enhance CARLA and Select Research Use Cases

Entity Type	Entity	Use Case	Link
Consultant and Academic Institution	Leidos; University of California, Los Angeles	Simulation platform to evaluate use of a regulations data interface for two selected scenarios: intersection right-turn-on-red and freeway left-lane use.	ADS Operational Behavior and Traffic Regulations Information Proof-of-Concept [88]
Academic Institution	University of North Carolina, Charlotte	Simulation for assessing online cooperative lane-changing decision-making and trajectory planning model for CAVs.	Online Cooperative Lane Changing Model of Connected and Autonomous Vehicles. [91]
Academic Institution	Columbia University; Rutgers University	Integrated model with SUMO to mine CAV driving behavior patterns using vehicle data sources and validate the model's results.	Driving Behavioral Learning Leveraging Sensing Information from Innovation Hub [92]
Academic and Research Institutions	University of California Berkeley; Karlsruhe Institute of Technology; University of Technology, Sydney; Peking University	Model to simulate a self-driving bus.	KIT Bus: A Shuttle Model for CARLA Simulator [93]

3.7.1.8 Summary

Key findings from the review of CARLA include [89]:

- CARLA supports the training, prototyping, and validating of autonomous driving solutions, including for both perception and control.
- It includes co-simulation features, allowing it to be integrated with many other tools such as Vissim and SUMO.
- The tool can model different weather conditions by configuring the dynamic weather settings, and it can model different sensors such as depth cameras, Radar, Lidar, etc.
- Additional skills and training may be required to make full use of the tool's functionalities.
- As an open-source tool, there is limited technical support available to users.
- It is not able to model thermal sensors [89].
- It is computationally demanding and requires at least a 6GB Graphics Processing Unit (GPU) or preferably a dedicated GPU capable of running Unreal Engine [94].
- CARLA requires significant disk space (at least 170 GB) to use, which may require investment in additional equipment to accommodate [94].

3.7.2 Vissim*

This tool is also discussed in the State of Practice report.

3.7.2.1 Tool Description

Vissim is a widely used multimodal traffic simulation software that can model and simulate urban traffic and public transit operations at the microscopic and mesoscopic levels. Vissim uses a behavior-based traffic simulation approach to model various components of the transportation system, including intersections, interchanges, arterial and freeway corridors, roadway networks, and public transit operations. It is stochastic and uses a discrete time-step approach in simulation. Vissim incorporates psychophysical perception models, such as the Weideman 74 and Wiedemann 99 models, to capture car-following behavior [95]. Additionally, it uses a rule-based, parameterized lane-changing model. Recent versions of Vissim provide the added capability of modeling new forms of mobility such as CAVs and MaaS, which have increased research capabilities for emerging ITS applications. Vissim, in conjunction with another PTV product called Viswalk, is able to analyze and simulate pedestrians [96], [97]. Vissim is a commercial tool and while students and researchers may be able to access limited to full versions of the tool for free, a license must be purchased to use the full version in practice [97].

3.7.2.2 Tool Category(ies)

Microscopic Simulation.

3.7.2.3 Primary Purposes/Objectives

Vissim is used by researchers for a variety of planning and operational purposes. At the planning level Vissim is used to develop and select preferred alternatives that can be used to determine viable novel improvements based on anticipated traffic growth and demand. At the operational level, Vissim is used for traffic impact analysis, transit center design, railroad grade crossing analyses, toll plaza evaluations, bicycle analyses, pedestrian analyses, and ITS assessments including for active traffic management, dynamic traffic assignment impacts, emissions modeling, access restrictions, and electrification [40], [98].

3.7.2.4 Scope (including applicable ITS component(s))

Vissim is used for link and network wide (comprising of arterials and freeways) analysis. This tool is also capable of modeling ITS applications. Examples include ramp metering, adaptive signal control, transit signal priority (light rail transit [LRT] and bus), traffic signal preemption at (or near) railroad crossing, emergency vehicle preemption, dynamic speed control, dynamic lane assignment signals, and changeable message signs [40].

3.7.2.5 Data Inputs/Requirements

Data required to model and conduct simulation using Vissim include the following [98]:

- Geometric Data and Analysis Data: Arrival distribution, auxiliary lane length, car-following model, entry traffic volumes, link length, desired speed distributions, turning speed (reduced speed areas).
- Travel Demand Data: O-D matrix for different user and vehicle classes including SOVs, HOVs, trucks, etc.
- Driver and Vehicle Characteristics: Driver acceleration/deceleration behavior, vehicle fleet type.
- Signal Timing Data: All-red time, controller, cycle length, left-turn phasing, cycle length, left-turn phasing, maximum green mode, maximum/minimum recall, minimum green time, offset reference, yellow time, flash don’t walk time, walk time.
- Pedestrian Data: Number of pedestrians crossing intersections.

3.7.2.6 Performance Measures/Outputs

Traffic operations performance measures/outputs derived from Vissim include Density (veh/ln/mi), Maximum Queue Length (ft), Microsimulation Delay (sec/veh), Space Mean Speed (mph), Time Mean Speed (mph), Travel Time (sec), 95th Percentile Queue Length (ft), Origin-Destination Pair Results, Pedestrian Analysis Results (Maximum/Minimum Number of Pedestrians, Density, Speed, Travel Time, Delay, etc.), Emissions, Fuel Consumption [98].

3.7.2.7 Known Entities that Use/Enhance the Tool and Select Research Use Cases

Table 12. Examples of Known Entities that Use/Enhance Vissim and Select Research Use Cases

Entity Type	Entity	Use Case	Link
Research Institution and Vendor	Karlsruhe Institute of Technology; PTV Group	Model to simulate and evaluate automated vehicles.	AV Modeling using Wiedemann's car Following [99]
Academic Institution	University of Central Florida	Model to investigate the effects of major key parameters on CO_2 emissions.	CO_2 Emissions [100]
Academic Institution	Indian Institute of Technology Bombay	Model for a heuristic adaptive traffic control algorithm for signalized intersections.	Adaptive Signal Controls [101]
Academic Institution	University of Buffalo, New York	Simulation model to estimate the effects of boarding conditions on bus dwell time and schedule adherence for passengers with mobility limitations.	Bus Transit Studies [102]

3.7.2.8 Summary

Key findings from the review of Vissim include:

- Its ability to simulate different road user classes such as buses, trucks, pedestrians, and bicyclists.
- Its incorporation of CAV features, including communications and cooperation among vehicles.
- Vissim is a high-fidelity multi-resolution software tool.
- Access to Vissim requires a paid license.
- Vissim has been noted as requiring more time to code input data than other traffic analysis tools; however, microscopic simulation tools all tend to require more time to code inputs than mesoscopic and macroscopic simulation tools [68].

3.7.3 CORSIM*

This tool is also discussed in the State of Practice report.

3.7.3.1 Tool Description

CORSIM is a microscopic traffic simulation tool that utilizes driver and vehicle behavior models and stochasticity to accurately replicate traffic and traffic control systems on a variety of roadways, including surface streets, freeways, highways, and interconnected networks [103]. This tool was first sponsored and developed by FHWA and is now part of the Traffic Software Integrated System (TSIS) collection of software tools managed by the McTrans Center at the University of Florida intended for use by traffic engineers and researchers [104], [105]. CORSIM consists of the integration of two models that can represent the entire traffic environment. NETSIM represents traffic on surface streets. FRESIM represents traffic on freeways. CORSIM implements a desired (safe) headway car-following logic as well as a mandatory versus discretionary lane-changing logic [103]. CORSIM provides its own interface and driver software. In addition to the user interface, the CORSIM driver provides access to a new output data processor. The output processor enables the user to accumulate user-selected statistics and summary data during multiple runs of the tool. It writes the collected data to an Excel workbook, a comma-separated file, and/or a tab separated file [106]. Overall, CORSIM is a versatile tool that provides transportation planners, engineers, and researchers with a comprehensive set of modeling capabilities. CORSIM is a commercial tool that requires a paid license to use.

3.7.3.2 Tool Category(ies)

Microscopic Simulation.

3.7.3.3 Primary Purposes/Objectives

CORSIM has been utilized worldwide by researchers and practitioners over the past 30 years primarily to conduct traffic operations analysis. For example, it can accurately replicate the spatial and temporal effects of congestion, model interactions between freeways and urban streets, and perform route assignments using DTA. The tool can also model interruptions to traffic flow, such as rail crossings, incidents, and work zones, and the effects they have on traffic flow. Additionally, CORSIM can analyze active traffic management strategies for arterials and freeways. The tool can also evaluate and test signal timing optimization in conjunction with TRANSYT-7F, Highway Capacity Software (HCS) tools, and other algorithms.

3.7.3.4 Scope (including applicable ITS component(s))

CORSIM is used for modeling and simulating vehicle and driver behavior as well traffic control systems on links and networks at the microscopic level. This tool is also capable of modeling ITS applications including ramp metering, adaptive signal control, transit signal priority, transit signal preemption at (or near) railroad crossings, emergency vehicle preemption, incident detection and management, managed lanes such as high occupancy vehicle (HOV) and HOT lanes, market penetration of CAVs with some degree of connectivity, etc.

3.7.3.5 Data Inputs/Requirements

Data required to model and conduct simulation using CORSIM include the following:

- Geometric Data: Lane width, lane length, horizontal and vertical grade, lateral curvature, number of lanes, entry and exit points, location of traffic control devices, turn bays, etc.
- Traffic Control Data: Signal timing data (controller type, cycle length, left-turn phasing, cycle length, left-turn phasing, maximum green mode, maximum/minimum recall, minimum green time, offset reference, yellow time, all-red time, flash don't walk time, walk time), lane markings, stop and yield signs, turning signs, etc.
- Traffic Flow/Travel Demand Data: O-D matrices, travel times, travel speeds, transit schedules, transit routes and stops, etc.
- Driver and Vehicle Characteristics: Driver acceleration/deceleration behavior, vehicle fleet type, etc.
- Pedestrian Data: Number of pedestrians crossing intersections.

3.7.3.6 Performance Measures/Outputs

Some of the performance measures/outputs generated by CORSIM include VMT, VHT, Average Delay (seconds), Density (vehicles/mile), Vehicle Throughput (vehicles/hour), Average Speed (km/hour), LOS, Average Travel Time (seconds or minutes), Bus Delay Per Vehicle (seconds/vehicle), Fuel Consumption (gallons), Pollutant Emission (kilograms/ mile-hour), etc. [105]

3.7.3.7 Known Entities that Use/Enhance the Tool and Select Research Use Cases

Table 13. Examples of Known Entities that Use/Enhance CORSIM and Select Research Use Cases

Entity Type	Entity	Use Case	Link
Research Institution	University of Texas at Austin Center for Transportation Research	Traffic operational analysis for different design alternatives along I-35 in Austin, TX.	IH-35 Operational Analysis [107]

Entity Type	Entity	Use Case	Link
Consultant	Leidos	Examination of the impacts of speed harmonization on I-394 in Minnesota.	Alternative Designs to Alleviate Freeway Bottlenecks at Merging, Diverging, and Weaving Areas. [108]

3.7.3.8 Summary

Key findings from the review of CORSIM include:

- Its ability to accommodate time-varying demand, simulate work zone behavior, bus operations, and various ITS.
- Its ability to support both 2D and 3D visualizations.
- CORSIM does not model toll booths and weigh stations, two-way left turn lanes, roundabouts, U-turns, or light rail.
- The tool is considered one-dimensional in the sense that vehicles do not adjust their speeds based on vehicles in adjacent lanes [105].
- Access to CORSIM requires a paid license and the tool may require additional training or skills to effectively use it.

3.7.4 TransModeler*

This tool is also discussed in the State of Practice report.

3.7.4.1 Tool Description

TransModeler is a microscopic traffic simulation software tool that can be used for various traffic planning and modeling tasks. It has the capability to simulate different types of road networks such as freeways and urban areas as well as analyze large-scale multimodal (e.g., trains, bicyclists, pedestrians, passenger vehicles, etc.) networks. With its ability to model and visually represent traffic systems in either a 2D or 3D GIS environment, TransModeler can demonstrate and evaluate traffic flow dynamics, traffic signal and ITS operations (e.g., CAV performance), and the overall network performance. The tool's base car-following model utilizes the stimulus-response General Motors model. However, users are able to implement the car-following model/logic of their choice, such as using the Constant Time Gap car-following model to more accurately model CAVs [109]. TransModeler provides a multiresolution hybrid simulation capability through which high fidelity microscopic simulation can be combined with mesoscopic and macroscopic simulation on specific network segments. Specified segments of interest within the network can be simulated with microscopic simulation while other segments or subnetworks can be simulated with lower resolution methods. This makes it possible for the tool to simulate very large networks without needing extensive computing power [110]. Another key feature of this tool is its ability to model evacuation plans and scenarios for response to natural disasters, hazardous spills, and other emergencies. TransModeler is a commercial tool that requires a paid license to use and is developed by Caliper Corporation.

3.7.4.2 Tool Category(ies)

Microscopic Simulation, Mesoscopic Simulation, Macroscopic Simulation, Multiresolution Hybrid Simulation.

3.7.4.3 Primary Purposes/Objectives

TransModeler has broad applications in planning for traffic operations and engineering design. These include simulations to compare impacts of operational strategies and design alternatives on a wide variety of road networks. This tool also has the capability to evaluate the impacts of future planning scenarios through integration with TransCAD, a travel demand forecasting software also developed by Caliper Corporation.

3.7.4.4 Scope (including applicable ITS component(s))

TransModeler can model and simulate links, networks, urban areas, counties, and regions [111]. This tool can simulate ITS strategies and technologies including active traffic management, reversible lanes, hard shoulder running, speed harmonization, adaptive ramp metering, variable speed limits, electronic toll collection, managed lanes, signal preemption, transit signal priority, actuated signal control, CAVs, etc. TransModeler can also model and simulate on-street parking [112].

3.7.4.5 Data Inputs/Requirements

Data required to model and conduct simulation using TransModeler include the following:

- Geometric Data: Lane width, lane length, horizontal and vertical grade, lateral curvature, number of lanes, entry and exit points, location of traffic control devices, turn bays, etc.
- Signal Timing Data: Signal timing data (controller type, cycle length, left-turn phasing, run yellow threshold, cycle length, left-turn phasing, maximum green mode, maximum/minimum recall, minimum green time, optimization minimum green, all-red time, etc.), lane markings, stop and yield signs, turning signs, pedestrian walk and flashing don’t walk signs, etc.
- Traffic Flow/Travel Demand Data: O-D matrices for different user and vehicle classes including SOVs, HOVs, trucks; travel times, travel speeds, transit schedules, transit routes and stops, etc.
- Driver and Vehicle Characteristics: Driver acceleration/deceleration behavior, vehicle fleet type, etc.
- Pedestrian Data: Pedestrian links, number of pedestrians crossing intersections.

3.7.4.6 *Performance Measures/Outputs*

Traffic operations performance measures/outputs generated from TransModeler modelling and simulation include VMT, VHT, Average Delay (seconds), Density (vehicles/mile), Vehicle Throughput (vehicles/hour), Average Speed (km/hour), Average Stops, Average Travel Time (seconds or minutes), Bus Delay Per Vehicle (seconds/vehicle), etc. [113].

3.7.4.7 *Known Entities that Use/Enhance the Tool and Select Research Use Cases*

Table 14. Examples of Known Entities that Use/Enhance TransModeler and Select Research Use Cases

Entity Type	Entity	Use Case	Link
Academic Institutions	Old Dominion University; George Mason University	Model to examine corridor-based tolling strategies for Virginia's express toll lanes.	Exploration of Corridor-Based Tolling Strategies for Virginia's Express Toll Lanes. [114]
Academic Institution	Louisiana State University	Integrated model with TransCAD to estimate the time-dependent evacuation behavior of households facing an oncoming hurricane.	Hurricane Evaluation Modeling Package [115]
Consultant	Resource Systems Group (RSG), Inc.	Evaluation of CAVs and ride-hailing by integrating TransModeler with an activity-based model.	Model Impacts of CAVs and Ride-Hailing with an Activity-Based Model (ABM) and DTA-An Experiment [116]
Academic Institution	Old Dominion University	Simulation model to test congestion mitigation strategies and evacuation scenarios in Virginia Beach, VA.	City-Wide Microsimulation Model for Virginia Beach [117]

3.7.4.8 *Summary*

Key findings from the review of TransModeler include:

- It has multiresolution hybrid simulation capabilities in which high-fidelity microscopic simulation can be intermixed with mesoscopic simulation.

- TransModeler is a GIS-based tool, which makes it simple to automatically load map layers and aerial imagery from Google Earth, Google Maps, OpenStreetMap, United States Geological Survey (USGS) Topographic Maps into the tool.
- Its ability to be integrated with trip-based and activity-based transportation planning models.
- The tool is integrated with HCS, which enables it to report simulation-based LOS metrics.
- Its ability to integrate with the travel demand forecasting tool TransCAD.
- The tool has built-in 3D visualization through Unity 3D Viewer.
- Outputs and MOEs from TransModeler usually require post-processing and formatting to be usable or interpretable [118].
- The tool is sensitive to path setups; if the path where the folder is stored on a machine is changed, or any component is renamed, the tool will require users to relink all the components to the project again (e.g., O-D matrices, turning movement tables, signal files, etc.), which can be time consuming especially if the work is done on different machines [119].
- There is limited access to electronic tool user manuals since they are accessible only when running the tool [119].
- Access to TransModeler requires a paid license and the tool may require additional training or skills to effectively use it.

3.7.5 Paramics*

This tool is also discussed in the State of Practice report.

3.7.5.1 Tool Description

Paramics is a fully scalable microsimulation software tool designed to model and simulate diverse transportation and traffic scenarios that has been used for dozens of applications around the world. This tool offers a realistic representation of a traffic network with 2D and 3D visualization of simulated entities [106]. It employs the psychophysical Fritzsche Model as its base car-following model and a gap acceptance theory-based model for its base lane-changing logic [120]. Paramics includes multimodality and has the ability to model passenger vehicles, buses, trams/trolleys, and pedestrians [121]. Paramics is a commercial tool and requires the purchase of a license to use [122].

3.7.5.2 Tool Category(ies)

Microscopic Simulation.

3.7.5.3 Primary Purposes/Objectives

Paramics is mainly used for modeling and simulating individual components of the traffic stream for planning and analysis purposes. It can model and simulate numerous traffic operations scenarios including traffic congestion, traffic signal control analysis, public transport operations, event planning, etc. It is also used to aid in the assessment of pedestrians' and bicyclists' safety and model and simulate infrastructure design alternatives as well as perform environmental assessments [121].

3.7.5.4 Scope (including applicable ITS component(s))

Paramics can model and simulate links, networks, urban areas, and entire cities at the microscopic level. It can perform public transportation simulation and it has a built-in 3D simulation visualization tool for generating output videos. This tool can model ITS strategies and components such as ramp metering, reversible lanes, dynamic lane management, hard shoulder running, active traffic management strategies, eco-speed harmonization, connected and automated vehicles, etc. It can also perform economic assessments and emissions modeling.

3.7.5.5 Data Inputs/Requirements

Data required to model and conduct simulation using Paramics include the following:

- Geometric Data: Lane width, lane length, horizontal and vertical grade, lateral curvature, number of lanes, entry and exit points, location of traffic control devices, turn bays, etc.
- Traffic Control Data: Signal timing data, lane markings, stop and yield signs, turning signs, etc.
- Traffic Flow/Travel Demand Data: O-D matrices, travel times, travel speeds, transit schedules, transit routes and stops, etc.
- Driver and Vehicle Characteristics: Driver acceleration/deceleration behavior, vehicle fleet characteristics, etc.
- Pedestrian Data: Pedestrian links, pedestrian counts, etc.

3.7.5.6 Performance Measures/Outputs

Some of the performance measures/outputs generated from Paramics modelling and simulation include VMT, VHT, Average Delay (seconds), Density (vehicles/km), Vehicle Throughput (vehicles/hour), Queue Length, Average Speed (km/hour), Average Stops, (seconds or minutes), Total Time Stopped for Public Transit (seconds or minutes), Passengers Boarding/Alighting, etc. [123]

3.7.5.7 Known Entities that Use/Enhance the Tool and Select Research Use Cases

Table 15. Examples of Known Entities that Use/Enhance Paramics and Select Research Use Cases

Entity Type	Entity	Use Case	Link
Academic and Research Institutions	Transport for London; Imperial College London; Flemish Institute for Technological Research; Austrian Institute of technology	Simulation model to assess the impact of traffic management on black carbon emissions.	Traffic Management and Carbon Emissions [124]
Academic Institutions	McMaster University; University of Toronto	Assessment of the potential mobility, environmental, and safety impacts of connected vehicles.	Potential Impacts of CV [125]
Consultant	SYSTRA Ltd.	Assessment of the potential accessibility, health, and financial impacts of the Dundee, Scotland Low Emission Zone (LEZ).	Low Emission Zone [126]

3.7.5.8 Summary

Key findings from the review of Paramics include:

- Its ability to perform large-scale microscopic simulations with detailed driving behavior such as acceleration/deceleration, lane-changing, and car-following at a time resolution of 0.1 sec [127].
- Its ability to test, simulate, and analyze the impact of various emerging ITS technologies (e.g., CVs) and traffic management strategies [125].
- Its ability to incorporate pedestrians and bicyclists in modeling and visualization [128].
- It has built-in 3D visualization.
- Simulations are potentially computationally intensive and require significant resources and time, especially for large-scale networks [127]. Additionally, Paramics has potentially time- and data-intense model development and calibration, depending on the size of network and complexity of scenario [129].
- It does not have the capability to output signal coordination timing [129].
- Outputs and MOEs from Paramics may require post-processing to be useable/interpretable.
- Access to the tool requires a paid license, and the tool may require additional training or skills to effectively use it.

3.7.6 MITSIMLab

3.7.6.1 Tool Description

MIcroscopic Traffic SIMulation Laboratory (MITSIMLab) is an open-source microscopic traffic simulation model developed by Massachusetts Institute of Technology's ITS Program. This tool enables evaluation of various traffic management and ITS strategies, including ATMS and route guidance systems, to assess their impact on traffic operations and help in their further refinement. MITSIMLab consists of travel and driving behavior models. The travel behavior models capture the driver's pre-trip and enroute route choices while the driving behavior models account for tactical and operational driving decisions, mainly acceleration and lane-changing [130]. MITSIMLab uses the Gazis-Herman-Rothery car-following model, which is based on the assumption that the follower's acceleration is proportional to speed, speed difference between leader and follower, and the headway. A gap-acceptance model is used to simulate lane change behavior [131]. While MITSIMLab is microscopic simulation tool, it can be integrated with mesoscopic simulation tools such as DynaMIT and Mezzo to create hybrid models [130], [132].

3.7.6.2 Tool Category(ies)

Microscopic Simulation, Multiresolution Hybrid Micro-Meso Simulation.

3.7.6.3 Primary Purposes/Objectives

MITSIMLab is used for the evaluation of impacts of alternative traffic management system designs at the operational level and assisting in subsequent refinement. Systems evaluated in MITSIMLab include ATMS and route guidance systems [133].

3.7.6.4 Scope (including applicable ITS component(s))

MITSIMLab is used for system, link, and segment (a part of a link with uniform geometry) analysis. This tool is also capable of modeling ITS applications. Examples include ramp metering, freeway mainline control, dynamic lane control signs, variable speed limit signs, portal signals at tunnel entrances, intersection controls, variable message signs, in-vehicle route guidance, etc. [130]

3.7.6.5 Data Inputs/Requirements

Data required to model and conduct simulation using MITSIMLab include the following:

- Travel Demand Data: Time dependent O-D trip tables, historical travel times.
- Traffic Control Data.
- Transit Network, Schedule Design, and Fleet Assignment.
- Traffic Flow Data: Real-time traffic and transit data from the surveillance system.

3.7.6.6 Performance Measures/Outputs

Some traffic related performance measures/outputs generated from MITSIMLab include Flow (veh/hr), Speed (mph), Density (veh/ln/mi), Queue Lengths (ft), Delay (sec), Travel Time (min). Transit system related performance measures/outputs include Total Passenger Travel Times (min), Number of Late Trips, Driver Overtime, Average Running Speed (mph), Travel Time Distribution, Average Dwell Times (min), Waiting Times (min), Travel Times (min), etc. [130].

3.7.6.7 Known Entities that Use/Enhance the Tool and Select Research Use Cases

Table 16. Examples of Known Entities that Use/Enhance MITSIMLab and Select Research Use Cases

Entity Type	Entity	Use Case	Link
Academic Institution	National University of Singapore	Simulation framework for crisis management.	Crisis Management [134]
Academic Institutions	MIT; University of Leeds	Model for cooperative lane-changing and forced merging behavior.	Arterial Lane Change Modeling [135]

3.7.6.8 Summary

Key findings from the review of MITSIMLab include:

- The tool enables detailed representations of routes and schedules, which allow transit and traffic operations in the simulated network to be sensitive to the variations in the route and schedule inputs [130].
- MITSIMLab provides real-time sensor data that mimics the surveillance capacities of the traffic management systems in an ITS environment [68].
- Its ability to model a wide range of traffic management system designs [136].
- Its lack of on-going updates by the original tool developer [137].
- The tool requires detailed data at an individual user level, including trajectories at high time resolution, for model calibration [130].
- Its lack of a functionality extension API as well as 3D visualization [136].
- Additional skills and training may be required to make full use of the tool's functionalities.
- As an open-source tool, there is limited technical support available to users.

3.7.7 INTEGRATION

3.7.7.1 Tool Description

INTEGRATION is a comprehensive traffic assignment, simulation, and optimization model that operates on a trip-based, microscopic level. It has the capability to simulate networks with up to 10,000 links and 500,000 vehicle departures. The model's primary purpose is to accurately trace the movement of individual vehicles from their origin to their destination, with a time resolution as precise as one deci-second. To achieve this, the model employs a departure simulation based on a time-varying O-D table. A time-varying, multi-class traffic assignment method is used to assign vehicles to the network. Once assigned, the model tracks the vehicles' movements at a deci-second level of detail, incorporating behaviors such as car-following, lane-changing, and gap acceptance. In particular, the model determines vehicle speeds by considering link-specific steady-state car-following relationships that are calibrated using data from field loop detectors [138]. The dynamics of a vehicle's movement from one steady-state to another are constrained by the model. Initially conceived as a mesoscopic model, INTEGRATION underwent development and transitioned into a microscopic model in 1995. In the U.S., it is distributed by McTrans Center at the University of Florida [139].

3.7.7.2 Tool Category(ies)

Microscopic Simulation.

3.7.7.3 Primary Purposes/Objectives

The INTEGRATION software is a microscopic simulation tool used to model and simulate many dynamic traffic phenomena, such as shock waves, gap acceptance, weaving as well as the impacts of traffic management strategies and the impacts of ITS applications on the transportation system. This software can also model energy, emissions, and crash risks [139].

3.7.7.4 Scope (including applicable ITS component(s))

The INTEGRATION software is a multimodal tool that can model light duty cars, light duty trucks, heavy duty trucks, buses, etc. It can model both freeways and arterials, including both signalized and unsignalized intersections. In terms of ITS applications, INTEGRATION can model eco-lanes, speed harmonization and dynamic speed limits, ramp metering, tolling and HOV lanes, adaptive traffic signal optimization, etc. [139].

3.7.7.5 Data Inputs/Requirements

Data required to model and conduct simulation using INTEGRATION include the following [140]:

- Roadway/Link Traffic Flow Data: Number of lanes, link speed, free-flow speed, jam density, length of link, link capacity, etc.

- Traffic Control Data: Traffic signal timing plan, traffic signs, traffic rules (e.g., HOV restrictions), etc.
- Travel Demand Data: Time series of aggregate O-D departure rates, vehicle headways (if available), traffic mix, etc.
- Incidents or Lane Blockages (if incidents are being modeled): Information on which lanes are blocked and lane capacity reductions.

3.7.7.6 Performance Measures/Outputs

Some of the performance measures/outputs generated by INTEGRATION include Link Travel Times (seconds or minutes), Vehicle Delay (seconds or minutes), Number of Vehicle Stops, Vehicle Fuel Consumption (liters), Vehicle Emissions (grams), Crash Rate and Severity, etc. [140]

3.7.7.7 Known Entities that Use/Enhance the Tool and Select Research Use Cases

Table 17. Examples of Known Entities that Use/Enhance INTEGRATION and Select Research Use Cases

Entity Type	Entity	Use Case	Link
Academic and Research Institutions	Virginia Tech; Qatar Mobility Innovations Center	Estimation of the effects of reduced traffic demand vehicle delays, fuel consumption, and emission levels.	COVID-19 Pandemic Impacts on Traffic System Delay, Fuel Consumption and Emissions [141]
Academic Institution	Virginia Tech	Simulation of a new logarithmic delay model to compute optimum cycle length that considers vehicle delay, fuel consumption, and tailpipe emissions.	Computing Optimum Traffic Signal Cycle Length Considering Vehicle Delay and Fuel Consumption [142]
Academic Institution	University of Idaho	Evaluation of vehicle performance in terms of fuel consumption at signalized intersections.	Field Implementation and Testing Eco-Traffic Signal System Applications [143]

3.7.7.8 Summary

Key findings from the review of INTEGRATION include [139]:

- It combines traffic assignment with microscopic simulation, which makes it possible to model and simulate pre-trip and enroute driver decisions.

- It is able to model and simulate large scale networks of up to 10,000 links and 500,000 vehicle departures as well as vehicle energy and emissions.
- It is able to compute 14 different crash risks, the level of vehicle damage, and passenger injury severity.
- Access to the tool requires a paid license.
- It is not able to model pedestrians and their interactions with vehicles on arterials.
- Additional skills and training may be required to make full use of the tool's functionalities.

3.7.8 SUMO*

This tool is also discussed in the State of Practice report.

3.7.8.1 Tool Description

Simulation of Urban Mobility (SUMO) is an open-source, microscopic, multimodal traffic simulation tool designed to handle large simulation scenarios. It allows for inter-modal simulation, such as including pedestrians with vehicular traffic, and comes with a large set of options for scenario creation. SUMO simulations are deterministic by default but there are various options for introducing stochasticity. The safe distance-based Krauss model is the default car-following model in SUMO; however, it allows for other models to be implemented. Additionally, four default types of lane-changes are implementable and include strategic, cooperative, tactical, and regulatory. [144] This tool is developed by the Institute of Transportation Systems at the German Aerospace Center. However, since it is open source, many entities and researchers are continuously working to extend its capabilities. One of such enhancements is the Veins framework. This includes a comprehensive suite of models to make vehicular network communication simulations as realistic as possible, without sacrificing computational efficiency/speed. By integrating the SUMO traffic simulation with the Veins framework, it is possible to model vehicular communication issues (e.g., radio interference, shadowing by static and moving obstacles, etc.) [145]. Such contributions are made available through the SUMO website, however they are not verified before being released and potential users are responsible for their own testing [146].

3.7.8.2 Tool Category(ies)

Microscopic Simulation.

3.7.8.3 Primary Purposes/Objectives

SUMO is mainly used for assessing operational strategies as part of planning by simulating vehicles at the microscopic level. In addition, the tool is also used for simulating vehicular communications (i.e., vehicle-to-everything [V2X] communications). This is done by joining SUMO to a communication network using a middleware (e.g., Veins, iCS, MOSAIC) [147].

3.7.8.4 Scope (including applicable ITS component(s))

SUMO can model and simulate links and large networks. In terms of ITS applications and technologies, SUMO can model and simulate adaptive signal control, variable speed limits, speed harmonization, hard shoulder running, CAVs, etc.

3.7.8.5 Data Inputs/Requirements

Data required to model and conduct simulation using SUMO include the following:

- Geometric Data: Lane width, lane length, horizontal and vertical grade, lateral curvature, number of lanes, entry and exit points, location of traffic control devices, turn bays, etc.
- Traffic Control Data: Signal timing data, lane markings, stop and yield signs, turning signs, etc.
- Traffic Flow/Travel Demand Data: O-D matrices, travel times, travel speeds, transit schedules, transit routes and stops, etc.
- Driver and Vehicle Characteristics: Driver acceleration/deceleration behavior, vehicle fleet type, etc.
- Pedestrian Data: Sidewalks, pedestrian route, pedestrian volume, etc.

3.7.8.6 Performance Measures/Outputs

Traffic operations performance measures/outputs generated from SUMO include Vehicle Throughput (vehicles/hour), Average Speed (km/hour), Average Stops, Average Travel Time (seconds or minutes), Density (vehicles/km), Occupancy (%), Average Delay (seconds), etc. [148].

3.7.8.7 Known Entities that Use/Enhance the Tool and Select Research Use Cases

Table 18. Examples of Known Entities that Use/Enhance SUMO and Select Research Use Cases

Entity Type	Entity	Use Case	Link
Academic Institutions	University of Virginia; Daegu Gyeongbuk Institute of Science and Technology	Simulation model to evaluate speed harmonization and merge control using CAVs on a highway with lane closure.	Speed Harmonization and Merge Control Using CAVs [149]

Entity Type	Entity	Use Case	Link
Academic Institutions	New York University; Ozyegin University	Assessment of the impacts of a gap acceptance behavior model for a stop-controlled intersection in New Jersey.	Simulation of Vehicles' Gap Acceptance Decision at Unsignalized Intersections Using SUMO [150]
Academic Institution	University of California, Davis	Model integrated with a vehicular Ad-hoc Network (VANET) simulator built on top of a communication network (OMNET++) to simulate and evaluate the performance of multimodal adaptive traffic signal control.	Enabling performance and security simulation studies of intelligent traffic signal light control with VENTOS-HIL [151]

3.7.8.8 Summary

Key findings from the review of SUMO include:

- The tool is open-source and does not require a paid license to access.
- Its ability to model large-scale microscopic simulations.
- Its ability to model and simulate multiple ITS applications (e.g., connected vehicle applications).
- Its compatibility with external software such as Vissim, Visum, MATSim, and others.
- Usage of SUMO requires prior knowledge of Python, C++, or command line programming as well as the ability to process XML files for initial setup and implementation.
- Its ability for users of the tool/researchers to extend the tool's capabilities through APIs.
- It only supports 2D visualization.
- Since it is an open-source tool, there is limited technical support available to users.

3.7.9 Aimsun*

This tool is also discussed in the State of Practice report.

3.7.9.1 Tool Description

Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks (Aimsun) is a multiresolution, multimodal AMS tool offering macroscopic, mesoscopic and microscopic level simulation under one platform [152]. Aimsun utilizes the Gipps' safe distance car-following model and a Gipps'-based decision process lane-changing model for microscopic simulation. This tool is a hybrid simulator which incorporates hybrid meso-micro and hybrid macro-meso models [153] to model large areas while having the ability to examine individual zones with a finer level of detail and fidelity [154]. Aimsun has built-in artificial intelligence, machine learning, and data analytics (visualization) capabilities. A version of this tool called Aimsun Live combines AI/ML techniques with simulation in real-time for predictive traffic management. Another version, called Aimsun Ride offers the capabilities of activity- and agent-based modeling [155]. The capabilities of Aimsun can be extended through its API, scripting, Aimsun Next's V2X software development kit (SDK) (utilizing Adaptive Cruise Control and Cooperative Adaptive Cruise Control car-following models), etc., making the tool suitable for many research endeavors [153]. Aimsun is an AMS software tool developed and licensed under the Yunex Traffic Group. The Aimsun software company offers free licenses for academic use, but a license must be purchased to use the tool in practice [156].

3.7.9.2 Tool Category(ies)

Microscopic Simulation, Mesoscopic Simulation, Macroscopic Simulation, Multiresolution Hybrid Meso-Micro Simulation, Multiresolution Hybrid Macro-Meso Simulation.

3.7.9.3 Primary Purposes/Objectives

Aimsun is a multiresolution simulation tool used by planners, engineers, and researchers for transportation policy analysis (e.g., investigating impacts of emerging mobility and technologies), transportation planning (e.g., lane closures, turn closures, speed reductions for traffic calming, ICM), multimodal transportation analysis (e.g., for vehicles, trains, pedestrians, cyclists), mobility analytics (special event planning and operations), real-time transportation management and predictive analytics, demand modeling, estimating the impact of emerging mobility technologies (e.g., EVs, shared AVs, CVs), energy and emissions modeling, and cost-benefit analysis of ITS technologies/strategies [157], [158].

3.7.9.4 Scope (including applicable ITS component(s))

Aimsun is used for modeling at multiple scale levels including the link and network level (comprising of arterials and freeways), urban area level, and regional levels. This tool is also capable of modeling ITS applications such as ramp metering, adaptive signal control, transit signal priority (LRT and bus), traffic signal preemption at (or near) railroad crossings, emergency vehicle preemption, dynamic speed control, dynamic lane assignment signals, and changeable message signs.

3.7.9.5 Data Inputs/Requirements

Data required to model and conduct simulation using Aimsun include the following:

- Geometric Data: Lane width, lane length, roadway grade, lateral curvature, number of lanes, entry and exit points, location of traffic control devices, etc.

- Signal Timing Data: Controller type, cycle length, left-turn phasing, cycle length, left-turn phasing, maximum green mode, maximum/minimum recall, minimum green time, offset reference, yellow time, all-red time, flash don't walk time, walk time, lane markings, stop and yield signs, turning signs, etc.
- Traffic Flow/Travel Demand Data: O-D matrices for different user and vehicle classes, modal split, travel times, travel speeds, transit schedules, transit routes and stops, etc. When agent-based models are incorporated into Aimsun Ride, population and activity/trip chain data is also needed as an input [155].
- Driver and Vehicle Characteristics: Driver acceleration/deceleration behavior, vehicle fleet type.
- Pedestrian Data: Number of pedestrians crossing intersections.

3.7.9.6 Performance Measures/ Outputs

Traffic operations performance measures/outputs generated from Aimsun modelling and simulation include Average Delay (seconds/mile), Density (vehicles/mile), Flow (vehicles/hour), Average Speed (mph), Mean Harmonic Speed (mph), Average Travel Time (seconds or minutes), Mean Queue Length (number of vehicles), Maximum Queue Length, Total Number of Stops, Fuel Consumption (liters), Pollutant Emission (kilograms), etc. [159]

3.7.9.7 Known Entities that Use/Enhance the Tool and Select Research Use Cases

Table 19. Examples of Known Entities that Use/Enhance Aimsun and Select Research Use Cases

Entity Type	Entity	Use Case	Link
Academic Institution	Chalmers University of Technology	Model for pedestrian traffic simulation.	Pedestrians Modeling [160]
Academic Institution	University of California at Berkeley	Simulation model to represent and test a coordinated ramp metering (CRM) control system's effects on a congested freeway (SR-99N in Sacramento, CA) with multiple vehicle classes.	SR-99N [161]
Academic Institution	Queensland University of Technology	Model for self-learning eco-speed control utilizing a machine learning approach.	Eco-speed Control [162]

Entity Type	Entity	Use Case	Link
Academic Institution	Munich University of the Federal Armed Forces	Model to simulate an autonomous taxi-system in Munich, Germany.	Autonomous Taxi [163]

3.7.9.8 Summary

Key findings from the review of Aimsun include:

- Its ability to model and simulate at microscopic, mesoscopic, and macroscopic levels.
- Its ability to perform multiresolution hybrid modeling such as for hybrid meso-micro and hybrid macro-meso scenarios.
- Its capabilities can be extended through multiple means, including the tool's API.
- Its ability to integrate its predictive capabilities with real-time traffic management.
- Its ability to provide decision support for transportation planning and policymaking.
- Its ability to discover, forecast, and deploy optimal ITS and traffic management strategies for ICM [164].
- It has an interface with built-in visualization options as well as the ability to integrate with other tools [165].
- Access to Aimsun requires a paid license and the tool may require additional training or skills to effectively use it.

3.7.10 Unity 3D

3.7.10.1 Tool Description

Unity 3D is a game engine that can be used to develop microscopic traffic simulation models. The engine provides a 3D graphics environment that can simulate various traffic scenarios and generate visualizations of the results. In traffic simulation modeling, Unity 3D can be used to develop realistic 3D representations of traffic scenarios, including roads, intersections, traffic signals, and vehicles. These models can incorporate realistic physics and behavioral models to simulate the movements and interactions of vehicles and pedestrians in a virtual environment. Microsimulation tools, equipped with car-following and lane-changing logic, can also be integrated with Unity 3D to provide realistic vehicle movements and behaviors. Unity 3D can also be used to visualize traffic simulation results in real-time, which can be useful for analyzing traffic flow, identifying bottlenecks, and testing the effectiveness of various traffic management and ITS strategies. Additionally, Unity 3D can be used to create immersive virtual reality (VR) simulations of traffic scenarios, which can provide a more realistic experience for users. Furthermore, this tool has a ML-Agents toolkit that allows for researchers to develop and integrate AI/ML algorithms into their models and simulations. Unity 3D is developed and licensed for a fee by Unity Technologies, however there is a free version of the tool that has limited functionality [166], [167].

3.7.10.2 Tool Category(ies)

Microscopic Simulation, Other - 3D Visualization.

3.7.10.3 Primary Purposes/Objectives

Unity 3D in traffic simulation modeling can be used to analyze traffic flow and test different traffic management and ITS strategies in a realistic and interactive virtual environment. However, it has mostly been used for 3D visualization of models as well as the creation of digital twins of environments and real objects such as vehicles and sensors [168].

3.7.10.4 Scope (including applicable ITS component(s))

Unity 3D is used for link- and network-wide modeling and simulation. This tool is also capable of modeling ITS applications and technologies. Examples include AVs, Vehicle-to-Infrastructure (V2I) communication, Vehicle-to-Vehicle (V2V) communication, and Infrastructure-to-Infrastructure (I2I) communication [169]. This tool has also been integrated with other microsimulation tools such as SUMO [166], [169].

3.7.10.5 Data Inputs/Requirements

Data required to model and simulate using Unity 3D include the following [167]:

- OpenStreetMap Data: Road networks (defined as inter-connected lines with latitude and longitude points), buildings (defined as polygons, with latitude and longitude for every point in the polygon), traffic signals, sidewalks, etc. [170]
- Vehicle Models Characteristics: Size, speed, acceleration, deceleration, torque, steering angle, etc.
- Traffic Control Systems: Traffic lights, stop signs, roundabouts, etc.
- Driver Behavior: Reaction time, following distance, lane-changing behavior, etc.
- Weather Conditions: Rain, snow, wind, etc.

3.7.10.6 Performance Measures/Outputs

Some of the performance measures/outputs generated by Unity 3D in the context of traffic simulation include Queue Lengths (ft) at intersections and bottlenecks, Average Speeds, Flow (veh/hr), Wait Times (min), etc. [171]

3.7.10.7 Known Entities that Use/Enhance the Tool and Select Research Use Cases

Table 20. Examples of Known Entities that Use/Enhance Unity 3D and Select Research Use Cases

Entity Type	Entity	Use Case	Link
Academic Institution	TU Dortmund University	Simulation for autonomous motorway traffic applied to help build motorway emergency corridors.	Emergency Corridor Building [172]
Academic Institution	KTH Royal Institute of Technology	Simulation to investigate the impacts of safe distance on traffic flow.	Investigating the impacts of safe distance on traffic flow [171]
Academic Institution	Johannes Kepler University; Eurecom Campus SophiaTech; Technical University of Madrid; Public University of Navarra, University of Applied Sciences, Austria	Simulation integrated with SUMO to evaluate V2X communication-based systems.	Evaluation V2X Communication-Based Systems [169]
Research and Academic Institutions	Oregon State University	Simulation that leverages digital twin and game-engine concepts to evaluate traffic and output effective visualizations.	Traffic Simulation and Visualization [173]

3.7.10.8 Summary

Key findings from the review of Unity 3D include:

- The tool has a limited capability free version available to users.
- The tool is a physics-based simulation tool that may be able to simulate vehicle maneuvers more accurately than purely traffic flow theory-based tools (e.g., car-following).
- The tool has a large amount of available documentation and online support [174].
- Unity 3D has a wide variety of available libraries and assets to develop models [175].

- It is primarily designed for game development, lacking many traffic-specific features found in dedicated traffic simulation engines. There is also limited understanding of its general traffic-specific modeling and simulation capabilities and potential areas of improvement.
- Its lack of ability for estimating some traffic-specific performance measures, such as intersection delay or traffic v/c ratio.
- Full access to Unity 3D requires a paid license, and the tool may require additional training or skills to effectively use it.

3.8 Other

Tools in this category are those that fall outside of the above TAT-based categories, but still fall within the AMS for ITS tools developed through and/or used in research scope of this report. These include:

- Autonomie
- StreetLight Data

The fidelity and/or resolution is presented for each tool in this tool category due to the tools' varying natures.

3.8.1 Autonomie

3.8.1.1 Tool Description

Autonomie is a vehicle energy simulator tool developed by Argonne National Laboratory. It is used to assess the energy consumption and cost of advanced powertrain technologies for conventional gasoline-fueled vehicles, hybrid EVs, plug-in hybrid EVs, battery EVs, and fuel cell EVs. Autonomie incorporates a physics-based model that simulates an assembly of components based on component-level analytical models to evaluate new powertrain technologies. The tool is primarily built in MATLAB and is free for research and teaching purposes. Autonomie enables users to assess vehicle dynamics, powertrain behavior, energy consumption, and control algorithms, aiding in the optimization of AV designs [176].

3.8.1.2 Tool Category(ies)

Other – Vehicle Dynamics Energy Simulation and Analytical Tool.

3.8.1.3 Primary Purposes/Objectives

The primary purpose of Autonomie is to predict and analyze fuel efficiency and cost. The tool is also used to estimate the energy, performance, and cost impact of advanced vehicle and powertrain technologies [177].

3.8.1.4 Scope (including applicable ITS component(s))

Autonomie can support a wide range of studies including analyzing various component technologies, sizing powertrain components for different vehicle requirements, comparing the benefits of powertrain configurations, optimizing both heuristic and route-based vehicle energy control and predicting transportation energy use when paired with a traffic modeling tool such as POLARIS. Emerging ITS vehicle technologies can also be assessed using this tool, including AVs [176], [177].

3.8.1.5 Fidelity and/or Resolution

Autonomie uses high-fidelity, fine-grain detail to simulate and estimate energy consumption of individual vehicles and their system components (i.e., powertrain and transmission).

3.8.1.6 Data Inputs/Requirements

Data required to simulate and perform analysis using Autonomie include the following:

- Vehicle Routing and Trajectory Data: From microscopic traffic simulation tools (e.g., SUMO, Aimsun, Vissim) or test data [176].
- Vehicle Parameters and Specifications: Mass, dimensions, aerodynamic properties, tire specifications, make, model, year, transmission type, engine type, and fuel type (e.g., conventional gasoline, battery EV, plug-in hybrid EV, fuel cell EV), etc. [177]
- Market Penetration Rates: Of various vehicle classes [178].

3.8.1.7 Performance Measures/Outputs

Some of the performance measures/outputs generated by Autonomie include Energy Consumption, Emissions, and Battery SOC.

3.8.1.8 Known Entities that Use/Enhance the Tool and Select Research Use Cases

Table 21. Examples of Known Entities that Use/Enhance Autonomie and Select Research Use Cases

Entity Type	Entity	Use Case	Link
National Laboratories	Argonne National Laboratory	Model to simulate energy consumption and cost reduction of future light-duty vehicles through advanced vehicle technologies anticipated through 2050.	Energy Consumption and Cost Reduction [177]

Entity Type	Entity	Use Case	Link
Academic Institutions	Georgia Institute of Technology; Kansas State University	Modal-based approach for estimating electric vehicle energy consumption in transportation networks.	EV Energy Consumption [179]
National Laboratory	Argonne National Laboratory	Future battery material demand analysis based on U.S. Department of Energy research and development (R&D) targets.	Future Battery Material Demand Analysis [178]

3.8.1.9 Summary

Key findings from the review of Autonomie include:

- Its ability to model the fuel efficiency and cost savings impacts of alternative fuel technologies at various market penetration rates [179].
- It is able to analyze fuel consumption and estimate emissions for more than 100 vehicle models ranging from light-duty to battery cell EVs [176].
- Acquiring required input data such as detailed vehicle parameters and specifications can be difficult.
- The tool requires continuous updates to incorporate the latest technological advancements in automotive sector (e.g., new technologies, connectivity, advanced sensors, novel control strategies).
- Since it is an open-source tool, there is limited technical support available to users.

3.8.2 StreetLight Data

3.8.2.1 Tool Description

StreetLight Data is a web-based on-demand mobility data-driven analytics platform that takes data from various sources to feed into analyses, outputting O-D matrices and travel times for select link studies. StreetLight data sources include CV data, Global Positioning System (GPS) data, commercial truck data, location-based services (LBS) mobility data, vehicular, bicycle, and pedestrian sensor data, land use data, parcel data, census characteristics (e.g., demographics, vehicle ownership, housing density), and road network characteristics from OSM. StreetLight Data implements several algorithms to infer modes and trips based on aggregated data. Mode assignment algorithms use heuristics and probabilistic methods based on movement patterns and spatial features that include distance, speed, circuity, road classification, presence of bike paths, proximity to parks, among others. The trip assignment algorithm then uses time stamps associated with LBS pings to determine trip starts and ends based on stationarity or changes in movement patterns [180]. Through the platform, an analyst can obtain volume of trips over different periods of time (e.g., day of the week, time of day) and for various vehicle types as well as identify trip time, length, speed and circuity, and trip purpose [181].

3.8.2.2 Tool Category(ies)

Other – Data-Driven Analytical Tool

3.8.2.3 Primary Purposes/Objectives

Data and metrics obtained from StreetLight Data can be used for various research and practice planning and traffic operational purposes. Examples include corridor planning, first and last mile studies, congestion studies, transportation demand management, bike and pedestrian studies, freight studies, and greenhouse gas emissions studies. Additional studies for which data and metrics from StreetLight Data have been used include traffic impact studies, detour and route planning, and multimodal planning [182]. StreetLight Data is also a source of O-D data that can be used for macroscopic simulation and transportation demand modeling [183].

3.8.2.4 Scope (including applicable ITS component(s))

Data and metrics for a variety of transportation facilities (ranging from isolated intersections to large transportation networks) can be obtained from StreetLight Data. Also, data and metrics derived from StreetLight Data analysis can be used for the evaluation of several ITS applications such as ramp metering, variable speed limits, and smart work zone operations [184].

3.8.2.5 Fidelity and/or Resolution

StreetLight Data is a high-fidelity tool capable of providing traffic data and analyses at various levels of granularity for various transport modes throughout the entirety of the day.

3.8.2.6 Data Inputs/Requirements

Data required to perform analyses in StreetLight Data include the following:

- Zone Data: Including gates, segments, and areas.
- Data Analysis Time Periods: Including day of week, weekday vs. weekend, time of day (AM, Mid-Day, PM), vehicle types, etc.

3.8.2.7 Performance Measures/Outputs

The following performance measures/outputs can be obtained from StreetLight Data:

Trip Attributes including Average Speed (mph), Travel Time (min), Distance (mi), VMT.

- Traveler Attributes including Trip Purpose and Census Demographics (e.g., household income, race, education of head of household, and family status).
- O-D Data for Pedestrian Metrics, Bike Metrics and Vehicular Metrics, as well as Annual Average Daily Traffic (AADT).

3.8.2.8 Known Entities that Use/Enhance the Tool and Select Research Use Cases

Table 22. Examples of Known Entities that Use/Enhance StreetLight Data and Select Research Use Cases

Entity Type	Entity	Use Case	Link
Research and Academic Institutions	Texas A&M Transportation Institute; Virginia Tech	Exploration of crowdsourced monitoring data for safety.	Data for Safety [185]
Academic Institution	University of Texas at Arlington	Assessment of the impacts of increased adverse weather events on freight movement.	Weather Impacts [186]
Research and Academic Institutions	Lawrence Berkeley National Laboratory; Marain Inc.; University of California, Davis; Emerging Futures, Inc.; The International Council on Clean Transportation	Assessment of energy use, emissions, grid integration, and cost impacts for private vehicles compared to shared vehicles, and automated electric vehicles for personal mobility.	Automated Electric Vehicles [187]

3.8.2.9 Summary

Key findings from the review of StreetLight Data include:

- Its ability to provides data and metrics for several transportation modes including cars, trucks, buses, rail, bicyclists, and pedestrians.
- It is a self-serve web platform, which allows analysts to access, analyze, and visualize data for a wide range of transportation facilities.
- The tool provides a quicker way to access traffic data compared to other methods that require installing software and possibly field equipment.
- It has been shown to have significant overestimation bias for low-volume roadways through validation studies [188].
- It relies heavily on the data points sampled from smartphone applications and GPS-enabled devices, which may be subject to potential bias and coverage issues [189].
- Access to StreetLight Data requires a paid subscription license, and the tool may require additional training and skills to effectively use it.

3.9 AMS for ITS Tools Literature Review Summary

AMS is a core competency in the field of transportation engineering. Transportation researchers continuously rely on, enhance, and build new AMS tools to understand prevailing safety, mobility, environmental, and other issues as well as develop, train, test, validate, and compare corresponding mitigating strategies and impacts of technology prior to field deployment. Additionally, AMS tools are employed to evaluate operational and control strategies as well as technology during deployment. A comprehensive review of literature of prevalent AMS for ITS tools that are used in/developed through research by agencies, vendors, laboratories/institutes, and academic researchers was conducted as part of this effort. Note, however, that an exhaustive review was not feasible. Additionally, as it is mentioned in the summary of the stakeholder feedback (**Chapter 4**), there are many in-house tools that are developed by researchers for very specific purposes and tools that are currently under development that were not possible to capture in this literature review. **Table 24** in **Appendix A** presents a consolidated list of the 20 identified prevalent AMS for ITS tools used in/developed through research by primary TAT category type. The following is a summary of key findings from the literature review.

- **Most of the tools used for research fall within the microscopic simulation category –** The most predominant principal category for AMS for ITS tools found to be part of the state of research is microscopic simulation. The category with the next most tools is mesoscopic simulation. Note that three tools (i.e., sketch planning tool EVI-X, travel demand modeling/macroscopic simulation tool Visum, and other category tool Autonomie) were found to not directly model, simulate, and/or analyze ITS applications. However, they can be integrated with the trajectories and/or other outputs from microscopic simulation tools (EVI-X, Autonomie) or integrated with travel demand modeling/macroscopic simulation tools (Visum) to include ITS applications, strategies, and/or technology components in their assessments.
- **Tools used for research tend to have high fidelity and resolution** – While there are a variety of AMS for ITS tools used in/developed through research, the majority of the ones

assessed are high resolution and fidelity micro-level tools. Many research entities have access to facilities with high computational and data storage capacities that can be potentially burdensome requirements to utilize the finer-detailed tools.

- **Most of the tools used for research can incorporate large-size networks** – Even though tools can be limited regarding the network size they can support (especially microscopic simulation due to the needed high level of detail and computational resources), only the mesoscopic simulation tool DynaMIT was particularly noted as being unable to simulate traffic for large networks. Note that large-scale networks are outside of the scope of Autonomie and several tools (i.e., Paramics, MATSim) were specifically identified as requiring significant computational resources to perform large-scale network simulation; typically, the larger the network size and higher the resolution, the longer the computation time is for AMS for ITS tools.
- **Much of the latest research conducted with AMS for ITS tools focuses on incorporating emerging ITS** – The latest research that utilizes/develops AMS for ITS tools focuses on better modeling, simulating, and/or evaluating the impacts of AVs, CVs, and CAVs as well as their associated sensors, infrastructure, communication protocols, electrification, control/operational strategies, etc. However, these research efforts are still in their exploratory/investigative stages and agreed upon/standardized AMS methodologies for emerging ITS are still needed.
- **Commercial tools used for research with capability extension mechanisms are more common than open-source tools** – Most of the reviewed research AMS for ITS tools are developed by private companies and require a paid license/subscription to use; however, some of these tools have free or discounted versions for academic and/or research use. These commercial tools are suited for research due to their various mechanisms (e.g., scripting, APIs, SDKs) that allow for researchers to extend their capabilities to develop, train, test, validate, evaluate, etc. various ITS components, strategies, technologies, etc. The open-source tools used for research are mostly sponsored by public agencies and/or academic research institutions. Compared to the commercial tools, the open-source ones typically have less technical support and documentation resources. These fewer resources for open-source tools can limit their usability.
- **Real-time predictive capabilities are becoming more prevalent in tools used for research** – Five of the twenty reviewed AMS for ITS tools used for research are identified as having real-time analysis, modeling, and/or simulation capabilities. In terms of predictions, two tools (DynaMIT and Aimsun) are noted as allowing for predictive transportation management analytics and one tool (Autonomie) predicts fuel efficiency and cost.
- **Minority of tools used for research have MRM capabilities** – Less than half of the AMS for ITS tools reviewed have multiresolution modeling capabilities. Some of the tools that do have these capabilities are those developed by the same company but at different scales. These include Vissim/Visum (micro-travel demand modeling/macro simulation) and TransModeler/TransCAD (micro-travel demand modeling/macro simulation). Additionally, TransModeler and Vissim have MRM capabilities on their own (hybrid meso-micro simulation). Other tools that can perform MRM capabilities on their own include DynaMIT (meso-micro simulation), MITSimLab (meso-micro simulation), and Aimsun (hybrid micro-meso and meso-macro simulation).

- **Safety analysis capabilities are limited in most tools used for research** – Performance measures related to safety (e.g., number of collisions, collision type, collision risk, collision severity, etc.) are only included in several of the tools used for research reviewed (INTEGRATION, CARLA). Mobility and efficiency analysis measures followed by environmental and energy measures are the most prevalent performance measures included in the tools.

3.9.1 Incorporation of Data Analytics and AI/ML in State of Research for AMS for ITS Tools

Data analytics and artificial intelligence/machine learning are increasingly being used in the development of AMS tools for ITS used in/developed through research. These methodologies can capture and analyze vast amounts of data generated by ITS applications and enable the simulation of more complex scenarios. AI/ML have the potential to improve the existing analysis, modeling, and simulation capabilities being in research. From the literature reviewed, several tools use AI/ML and/or data analytics for research purposes. Aimsun combines AI/ML techniques with high-speed simulations to predict future traffic conditions based on which appropriate mitigation strategies can be implemented [190]. Additionally, TransCAD employs ML decision tree algorithms for population synthesis, CARLA uses ML for AV vehicle behavior, StreetLight Data leverages a data-driven analytics platform to determine O-D matrices and travel times, and Unity 3D has a ML-Agents toolkit to enable researchers to develop and implement AI/ML algorithms into their models and simulations.

These advanced techniques are also emerging as useful methods in research to apply real-time traffic data to make predictions and provide recommendations on traffic management and control, including traffic signal timing, lane closures, and emergency response. Data analytics and AI/ML techniques (e.g., support vector machines (SVM), long short-term memory (LSTM) neural networks, k-nearest neighbor (KNN) clustering, and decision trees for classification and/or regression purposes) can also be used to optimize traffic management systems, including adaptive traffic signal control, route guidance, and incident management [191]. Several of these methodologies are currently being researched and developed to serve as standalone frameworks/tools or extensions to existing AMS tools. A few of these efforts are discussed below.

- Data2DemandModel – Researchers at the Arizona State University have developed an AI tool called Data2DemandModel, which showcases how deep learning techniques can be combined with the traditional four-step process in transportation modeling. This is achieved through a computational graph-based approach that utilizes multiple data sources. The tool incorporates a multi-layered Hierarchical Flow Network (HFN) representation to model various levels of travel demand variables such as trip generation, origin/destination matrices, path/link flows, and individual behavior parameters. The proposed network structure can integrate different data channels from sources like household travel surveys, smartphone devices, global position systems, and sensors. Based on a comparative analysis, it has been shown that this methodology can effectively integrate various data sources and provide a consistent representation of demand [192].

- I-24 MObility Technology Interstate Observation Network (MOTION) – I-24 MOTION is a testbed developed by the Tennessee DOT to understand how all types of vehicles interact with each other and the state's infrastructure. The project aims to install more than 300 ultra-high-definition cameras along a six-mile stretch of I-24. These cameras will capture images of every vehicle passing through, and with the help of AI trajectory algorithms developed by Vanderbilt University, the data collected will be transformed into a digital model that provides details on the behavior of each vehicle to reveal new insights into the relationship between traffic flow and individual vehicle behavior. Some potential users of this testbed include researchers, traffic simulation software developers, ITS product manufacturers etc. [193].
- Regional Multi-Modal Mobility Program (RM3P) – RM3P is a research-to-deployment program that fosters collaboration and relies on data to enhance the safety, consistency, and efficiency of travel in Virginia. It utilizes real-time information from both public and private entities to empower the public with informed travel decisions. The program incorporates advanced technologies, such as a Data-Exchange Platform that gathers and shares real-time and past travel information across various modes of transportation. Additionally, an AI-Based DSS is employed to anticipate the effects of disruptions on the transportation network and offer coordinated response strategies to relevant agencies [194].
- Trajectory Conversion Algorithm (TCA) – The data analytics TCA software is an outcome of research and serves as a tool for experimenting with different approaches to generate, transmit, and store data from Connected Vehicles. It makes use of inputs such as vehicle trajectory data or Vissim output, roadside equipment (RSE) location information, cellular coverage, and strategy details. These inputs are utilized to create a series of simulated snapshots that resemble the data produced by connected vehicles. Equipped vehicles can then send out various types of messages like Probe Data Messages (PDMs), Basic Safety Messages (BSMs), Cooperative Awareness Messages (CAMs), or Signal Phase and Timing (SPaT) messages using either Dedicated Short-Range Communication (DSRC) or cellular networks [195].
- Regional Integrated Transportation Information System (RITIS) – RITIS is a platform designed to provide situational awareness, data storage, and analytical capabilities to a diverse user base including transportation officials, first responders, planners, and researchers. It offers a comprehensive set of analytical tools that enable a wide range of capabilities and insights, ultimately reducing the costs associated with planning and research. RITIS also fosters information sharing, collaboration, and coordination across different agencies. The platform has the capability to integrate data from various sources including transportation and public safety systems, the private sector, and the military. This data is securely fused in the cloud and then distributed to authorized users through interactive websites, applications, data feeds, and APIs. The types of data that RITIS can handle include traffic volume, speed, events, work zones, incidents, crowdsourced Waze data, automated vehicle locations, signal timing plans, O-D and trip data, as well as connected vehicle and autonomous vehicle data, among others [196].
- CARMA Platform – The FHWA initiative CARMA actively contributes to the advancement of Cooperative Driving Automation (CDA) through collaboration and the development, testing, and evaluation of open-source software (OSS) platform. CARMA looks to facilitate the incorporation of communication among connected vehicles, pedestrians, bicyclists, scooters, and infrastructure devices. Furthermore, it aims to enhance the safety, security, data utilization, and utilization of AI/ML in automated driving technology. The CARMA Platform is

distributed as a collection of distinct independent core and support products/packages, hosted in separate GitHub repositories. These packages enable the operation of the CARMA Platform with different hardware configurations and support various modes of operation [197].

- Dense deep-reinforcement-learning (D2RL)-Based Intelligent Testing Environment – The University of Michigan Transportation Research Institute/MCity developed a D2RL-based intelligent testing environment to quantify and validate the safety performance of AVs, which has proven to be time and resource cost-prohibitive in real-world driving environments. The developed testing environment incorporates AI/ML-driven background agents trained to quickly assess the safety performance of AVs. The D2RL-based approach optimizes Markov decision processes by eliminating non-safety-critical states and reinforcing critical connections, which in turn, increases information density in the provided training data [198].

3.9.1.1 Data Analytics and AI/ML Gaps and challenges

There are some challenges associated with the use of data analytics and AI/ML in AMS for ITS tools used for research. These include [199], [200]:

- New developments in AI/ML in recent years have made algorithms and models increasingly complex (e.g., deep learning), making it more difficult for domain experts to understand their outputs and the reasoning behind them. The explainability/interpretability of models is of utmost importance.
- There is increasing risk of bias, which can lead to inaccurate and unusable outputs if not intentionally accounted for. For example, biased data collection can lead to unfair/unequitable modeling outcomes such as for AI-powered traffic signal application models relying on data from an unrepresentative subset of the population to construct AI prediction algorithms. Concerns arise specifically with smart intersection crossing, as there is a risk of excluding pedestrians with visual impairments or cognitive and physical disabilities, who may require more time to cross a particular street. If the data fails to include all VRUs, the prediction algorithm may potentially discriminate and be biased against them.
- There may be implications for privacy preservation concerns. For example, applications for in-vehicle systems may require additional regulations to ensure personal and private data are not at risk for being leaked during research development and during deployment.

3.9.2 Applicability of Capability Maturity Models and Technology Readiness Levels to the State of Research for AMS for ITS Tools

Based on an examination of publicly accessible literature, it was determined that AMS for ITS tools used in/developed through research lack applicable comprehensive capability maturity models and technology readiness frameworks. Due the inherent exploratory nature of research, CMMs do not appear to be applicable to research and TRLs may be used to understand general needs that drive research but have limited to no applicability beyond that [12]. The subsequent findings outline the key observations regarding the utilization of capability maturity models and technology readiness levels in the context of AMS for ITS tools used for research:

- Although FHWA's Traffic Analysis Capability Maturity Framework offers guidance on a systematic method to identify traffic analysis and AMS capabilities, as well as technology readiness levels, there is a lack of publicly accessible evidence regarding its application in research [201]. Publications on how agencies have used this framework are forthcoming.
- Numerous agencies have developed guidance documents and tools to assist their practitioners in choosing the most suitable AMS tool based on various operational conditions and other project-specific characteristics (e.g., Virginia Department of Transportation's (VDOT) guidance tables and Software Selection Tool (SST) to aid in the selection of AMS tools [98]; Ohio Department of Transportation's (ODOT) guidance for selecting appropriate tools [202]; the Kentucky Transportation Cabinet's Traffic Analysis Software Selection Tool to determine the most suitable tools for their needs [203]. However, these guidance documents have limited to no applicability to AMS for ITS research tool use or development.
- Certain agencies only have a publicly-facing list of approved AMS tools without providing comprehensive guidance regarding the specific operational conditions that govern their usage, such as New York State Department of Transportation (NYSDOT) [204]. The process for how to get a tool developed through and/or used in research added to such a list is not public knowledge.
- It appears that TRLs may not be the most conducive method for assessing AMS for ITS tools' maturity but may instead look to use them to help assess the maturity and/or readiness for implementation of specific technologies [12].
- As a result, it is important to engage with agencies, vendors, and researchers to understand their internal procedures and approaches when it comes to evaluating the capability maturity and technology readiness level frameworks AMS for ITS tools.

4 Stakeholder Feedback

A volunteer group of expert stakeholders was established from representatives of state, local, and regional agencies, consultants, vendors, and academia who perform and/or support research in the area of AMS for ITS tools. The ITS JPO's AMS Program support team conducted one-on-one discussions with members of the expert group of stakeholders to obtain their inputs on AMS for ITS tools that are part of the state of research, specifically regarding what tools they use/develop/enhance, how they use them, what they think are the limitations of these tools, and what they see as emerging trends or future direction of these tools. Discussions were held with a total of 20 stakeholders from 15 organizations, including three state DOTs, two consulting firms, three tool development vendors, and seven academic universities. The full interview questionnaire for the researchers as well as the research-specific practitioner questions and research-specific tool developer questions used to guide the interviews can be found in **Appendix B**. A general summary of the feedback received is summarized below.

4.1 Types of Analysis, Modeling, and/or Simulation Tools Used in Research

- Tools that the interviewed researchers use/enhance for a variety of ITS analysis, modeling and/or simulation purposes are listed below. These tools are also included in the literature review.
    - SUMO for microscopic simulation, emerging technologies, and communications modeling.
    - TransModeler for multimodal transportation planning, microscopic simulation, mesoscopic simulation, hybrid multiresolution simulation.
    - MATSim for mesoscopic activity-based demand modeling.
    - POLARIS for microscopic-level environmental energy and emissions analysis.
    - Vissim for analysis/modeling of emerging mobility and technologies, multimodal transportation planning, microscopic level modeling, time horizon predictions, modeling the incorporation of real-time applications with data feeds.
    - Visum for planning related to emerging technologies and travel demand modeling.
    - DTALite for mesoscopic-level modeling, improving traffic signal representation, dynamic traffic assignment.
    - Paramics for microscopic simulation of emerging technologies, including automated vehicles.

  - Aimsun for multimodal transportation planning, microscopic-level modeling of emerging technologies and vehicles, travel time prediction, impact analysis of EVs.
  - TransCAD for macroscopic-level travel demand analysis and forecasting/planning.
  - TRANSIMS for microscopic-level modeling and simulation.
  - Unity 3D for microscopic simulation.
  - CARLA for microscopic simulation of emerging technologies, including ADS and platooning.
- Most of the above software tools are not open-source and require a paid license and/or subscription to access, which can be limiting in terms of the number and breadth of tools that researchers working for resource-constrained agencies are able to utilize.
- The majority of the interviewees indicated that they have enhanced or are in the process of enhancing out-of-the-box tools (such as those listed above) and/or developed/developing their own in-house software or tools to better suit their needs. For example, most of these interviewees cited using APIs for extending existing tool capabilities. Several researchers also indicated that they are building custom features to enhance AMS for ITS tools' data handling capabilities, such as machine vision modules for collecting and processing data from cameras. Moreover, the following customized tool developments were mentioned:
  - Veins, a framework for running vehicular network simulations.
  - Achieving sustainable train energy pathways (A-STEP), a modeling tool to assess energy and emissions for rail-based freight transportation.
  - OpenStreeMap to General Modeling Network Specification (osm2gmns), an open-source Python package used to obtain and model transportation networks and then output them to standard GMNS format.
- Additional tools that the researchers identified are listed below. These tools are not expanded upon further in the literature review because they do not include at least one component of ITS, are still in the development process, there have not been published research use cases within the last five years, and/or prevalent research use cases are not yet available.
  - Trafficware's Synchro and SimTraffic for transportation network and system optimization, traffic signal optimization.
  - PTV's Optima for short term prediction related to analysis/modeling of emerging mobility and technologies, energy and emissions analysis/modeling, traffic safety analysis/modeling.
  - PTV's Flows expected as a lightweight version of PTV Optima that will incorporate ML components to estimate travel times and delays using historic data.
  - PTV's Vistro for transportation network and system optimization, traffic impact assessment.
  - Numetric's Traffic Safety Analytics Platform for safety analysis.
  - IBM's SPSS and StataCorp's Stata for data analysis.

- Realtime Technologies' SimCreator for real-time vehicle dynamics modeling and simulation.
- U.S. DOT's OpenCDA for cooperative driving automation simulation.
- Bentley Systems' CUBE for macroscopic transportation planning assignment.

4.2 Applicable Use Cases

- Researchers reported performing traffic modeling at macroscopic, mesoscopic, and microscopic resolutions and that they are increasingly performing more multiresolution modeling. Some researchers indicated they are currently working on real-time hybrid modeling while others emphasized this type of modeling for future direction.
- Compared to the interviewed practitioners, the interviewed researchers are involved in more emerging areas of AMS for ITS, specifically AI and ML. Example use cases include embedding deep learning into demand and choice modeling methods, vision-based vehicle detection via surveillance video, and using ML algorithms to leverage census data, employment data, and geospatial data from OpenStreetMap for policy and planning. Interviewees also reported heavily using AI/ML for data processing and cleaning prior to feeding data into a model. For real-time data that are coming from sensors in the field, AI/ML are utilized for detecting anomalies in the data and helping finetune the data inputs. Additionally, some researchers noted their recent creations of digital twins so that they can better handle future planning and analysis transportation and traffic scenarios, such as those involving emerging ITS.
- Performance measures most often considered include mobility indicators such as queue length, delays, vehicle hours, travel times, speeds, flow, bottleneck performances, route choice, etc. Other commonly modeled measures included environmental indicators such as fuel and energy consumption, pollution, and emissions. These sets of performance measures are also the most prevalent ones found through the literature review. LOS is used often as well to indicate mobility; however, this measure is not as popular in research because it fails to account for the mobility of VRUs, among other factors. Safety measures were largely absent from the discussions (see crash analysis under "Limitations, Gaps, and Challenges"). One researcher noted their coupling of the Automated Traffic Signal Performance Measures (ATSPM) [205], which focus on targeted traffic signal maintenance and improving operations and increasing safety through re-timing, with microscopic simulation tools to expand the number of performance measures available to evaluate a system as well as bridge the gap between traffic signalization design/optimization and implementation. Furthermore, several researchers noted their preferences to use performance measures are easy to collect, meaningful, and easy to explain. They further elaborated that they use direct outputs of analysis or their cumulative distribution functions as opposed to averages or measures resulting from complicated post-processing methods.
  - One researcher highlighted FHWA's Congestion and Bottleneck Identification (CBI) Tool [206] as being particularly helpful for determining congestion duration and spatial queue lengths. The tool produces both numeric and graphical measures to support the comparison and ranking of traffic bottlenecks that go beyond bottleneck rankings currently available in the industry by accounting for both intensity and variability.

4.3 Input/Calibration Data

- Many researchers indicated they still rely on field data from traditional ITS data sources, such as loop detectors, microwave sensors, and signal controllers. At the same time, they are utilizing emerging data sources, such as data collected from mobile devices serving as vehicle "probes" and drones. Feedback suggests that volume data, in particular, has become increasingly difficult to collect, especially since the COVID-19 pandemic. Furthermore, researchers indicated that they collect data from instrumented vehicles as well as passenger vehicle, truck, and bicycle simulators. Interviewees reported supplementing field and simulator data with the following data from other sources, including:
    - Open-source Data: Researchers reported using online aerial datasets such as OpenStreet Map and Google Earth for geometric data and FHWA's National Performance Management Research Data Set (NPMRDS) and state agency-specific detector/sensor data, such as that from California Department of Transportation's (Caltrans') Performance Measurement System (PeMS), for travel times, queues, volumes/flows, speeds, and densities, census data for rural/urban demographic data, and the National Household Travel Survey for travel demand data. Despite being nearly two decades old, FHWA's Next Generation Simulation (NGSIM) dataset remains the most popular vehicle trajectory dataset used by the research community and was referenced by several researchers. Traffic signal data was also reported from several public data sources.
    - Proprietary Data: Many of the researchers had greater access to proprietary data sources compared to the practitioners. Specifically, researchers noted that they have obtained INRIX data to enhance their models, including data on travel times, speeds, and bottleneck locations, as well as non-traditional data on wiper status, fog lamps status, pavement status, etc. Additionally, some researchers/vendors the use of StreetLight data for understanding traffic patterns and TomTom data for building models from big data sources. Researchers also mentioned leveraging vehicle trajectory data from Wejo, citing the appeal of their trajectory data being in raw form and not just averages, as is standard. At least one researcher mentioned that they were experimenting with premium Point of Interest (POI) data sold by private companies like Veraset and SafeGraph to calibrate their models.

4.4 Limitations, Gaps, and Challenges

- There was general consensus that there is a lack of empirical driver behavior data (e.g., regarding car-following, lane-changing, speed compliance, route choice, how drivers react to and interact with emerging ITS CVs, AVs, and CAVs, mixed environments with the present of VRUs, driver behavior under different congestion levels and when incidents occur, etc.). This makes it particularly difficult to model advanced ITS, such as AVs and CAVs, where models are heavily based on underlying assumptions. Additionally, several researchers noted a desire to gain access to data collected by the FHWA CARMA Program [197] to help bridge this gap.
- Data standards and adoption of the standards are important to be able to incorporate emerging ITS data in AMS tools. Another major shortfall noted was the lack of a standard or

benchmark for system level analysis of CAVs. Impact assessment studies in today's literature typically use varying scenarios and standards for driver behavior. Lack of adoption or participation with standards or benchmarks can lead to AMS tools not having enough transparency and/or being contradictory to each other, reducing the overall credibility of findings.

- Several interviewees noted that current AMS safety models and performance measures are underdeveloped, creating challenges for performing crash analysis (crash probabilities, crash predictions, near-miss analysis). With the growing trend of mixed-use developments, agencies articulated the need for additional research on how vehicles interact with vulnerable road users.
- Other use cases were identified as being under researched. One such use case is understanding the impact of cyber-attacks on traffic flow. Though there is potential for infrastructure and vehicles to be compromised, current tools do not allow the modeling of this.
- Researchers noted that while AI/ML are essential to the improvement of AMS for ITS tools moving forward, these techniques can be misused and be difficult to interpret. One interviewee noted a need to combine the use of AI with physical and behavioral models.
- Interviewees conveyed that there is a disconnect when it comes to promotion and adoption of AMS for ITS research with agencies and their practitioners.
- Several interviewees conveyed that they would like to see U.S. DOT help with establishing a clearinghouse of best practices for AMS for ITS. Similarly, one interviewee expressed the need for an open-source data hub that enables the exchange of data among multiple resolutions of AMS tools to save users time between inputting data, modeling, and then display results in a common format. Another interviewee noted a desire to have an accessible connected web-based and/or cloud-based AMS tool environment in which multiple researchers at various locations can collaborate and work together.

5 Gaps and Challenges in AMS for ITS Tools Used in Research

This chapter summarizes gaps and challenges in the representative review of AMS for ITS tools used in/developed through research within the past three to five years based on the review of publicly available literature on the relevant tools and discussions with the group of expert stakeholders. Additionally, a qualitative impact versus difficulty analysis [207] activity was conducted with the project team and federal stakeholder AMS for ITS SMEs to help prioritize which gaps and challenges could best be addressed by the ITS JPO's AMS for ITS Program. During the activity, each SME scored each gap/challenge based on its potential impacts (1=low impact, 5=high impact) regardless of its potential difficulty and difficulties in addressing (1=low difficulty, 5=high difficulty) regardless of its potential positive impact using the Mural Software platform. The scores from all SMEs were then averaged and divided into four distinct categories: "best bets" (lower difficulty with higher impact), "quick wins" (lower difficulty with lower impacts), "low priority" (higher difficulty with lower impact), and "long shots" (higher difficulty with higher impact). Findings from the activity were then used to inform Program goals, objectives, and activities.

A summary of the gaps and challenges with their descriptions, notes about whether they were identified in the literature review, stakeholder interviews, or both, along with potential impacts and difficulties with their solutions are presented in **Table 23**. 11 gaps/challenges were identified and consolidated. Note that the order in which the gaps and challenges are presented and assigned ID numbers is not indicative of their priority. **Figure 1** presents the qualitative graphical results based on averaged scores from the impact versus difficulty federal SMEs activity. To reiterate, potential impacts are first identified as positive outcomes that may be realized if the gap/challenge could be addressed regardless of any potential difficulty, including cost. Potential difficulties are then identified as likely costs, time commitments, labor efforts, complexity, etc. that would be experienced by addressing the gap/challenge regardless of the potential impact.

Table 23. Summary of Identified Gaps and Challenges in AMS for ITS Tools Used in Research and Potential Impacts and Difficulties in the ITS JPO's AMS for ITS Program Addressing Them

Gap/ Challenge ID	Gap/ Challenge Short Name	Gap/ Challenge Description	Identified in Literature Review and/or Interviews?	Potential Impact of Addressing Gap/ Challenge	Potential Difficulty in Addressing Gap/ Challenge
1.	Lack of driver behavior and multi-modal empirical data	Lack of available empirical driver behavior, pedestrian, bicyclist, other micro-mobility-specific data and/or processes and measures to consistently validate advanced AMS for ITS tools (e.g., for modeling ITS such as CAVs). Lack of understanding of driver behavioral response to ITS (e.g., DMS, dynamic tolling, managed lanes, CAVs) and corresponding field-collected empirical field-collected data (e.g., raw trajectory open-source data for	Interviews	• More accessible open-source data that fill this data gap. • Increased accuracy and reliability of tools calibrated, validated, and tested using these data. • Development of more robust AMS for ITS tools based on these data.	• Cost for collecting/acquiring data and providing sufficient documentation. • Cost for storing and maintaining data. • Cost for providing support to users of the collected data. • Protecting against redundant data collection efforts.

Gap/ Challenge ID	Gap/ Challenge Short Name	Gap/ Challenge Description	Identified in Literature Review and/or Interviews?	Potential Impact of Addressing Gap/ Challenge	Potential Difficulty in Addressing Gap/ Challenge
		non-equipped vehicles, CVs, AVs, CAVs, VRUs, and mixed environment traffic).			
2.	Limited interfaces, visualizations, and illustrative capabilities	Limitations with tool user interface, visualization functionalities, and illustrative capabilities	Literature: BEAM CORE, MITSimLab, SUMO; and Interviews	• Increased ability of practitioners and researchers to understand and use tools with less intuitive GUIs and incorporate GUIs into new/enhanced tools. • Better understanding of/ analysis capabilities for inputs, tool functionalities, and outputs.	• Cost for providing guidance and/or training that addresses user interface and illustrative capability shortfalls. • Cost for creating a universal visualization tool to provide such capability across tools.
3.	Gap in knowledge transfer between research and practice application	Lack of guidance for how to promote and facilitate adoption of research-developed AMS for ITS tools and methods with state agencies and practitioners	Interviews	• Streamlined process/guidelines for the steps and scenario/use case applications needed to transition AMS for ITS tools from research to practice. • Consistent scenario/use case definitions that will aid in re-creating results with research AMS for ITS tools to better understand a tool's suitability for practice.	• Cost to develop and update use cases and guidance for a process to apply AMS for ITS tools developed through and used in research to practice. • Difficult to generalize such a process to transition from research to practice due to the breadth of applications and need to be able to trust and verify tools before adopting them in practice.

Gap/ Challenge ID	Gap/ Challenge Short Name	Gap/ Challenge Description	Identified in Literature Review and/or Interviews?	Potential Impact of Addressing Gap/ Challenge	Potential Difficulty in Addressing Gap/ Challenge
				• Faster adoption of new and enhanced AMS for ITS tools in practice. • Improved AMS for ITS tool functionalities.	• Difficult in establishing scenario/use case baseline results. Analysis should be tool-agnostic but that is often not the case when trying to re-create results, making it difficult to understand which tool's results are better when multiple tools output significantly different results. • Can be difficult to get researchers and practitioners to want to work together.
4.	Tool scope limitations	Tool scope limitations (e.g., facility types, lane designation types, transit modes, micro-mobility modes, shared mobility, realistic collision and/or near-miss incorporation, emerging and enhanced ITS components and strategies, safety analysis,	Literature: EVI-X Suite, TransCAD, DTALite, Autonomie, DynaMIT, POLARIS, CARLA, CORSIM, Paramics, INTEGRATION, Unity 3D; and Interviews	• Continuously updated guidance, training, and/or use cases for which tools are best applicable for which scenarios could increase understanding and appropriate tool use, and more focused tool developments. • More inclusive cyber-physical modeling systems with the ability to model cyber-attacks. • More accurate incorporation of collision	• Cost for developing guidance and/or training and updating them as advances are made and new/updated software are created. • Breadth of tools used in practice is vast, presenting difficulty in providing support that adequately meet agency/practitioner/researcher needs. • Need for ITS JPO to show impartiality towards the vendors and researchers

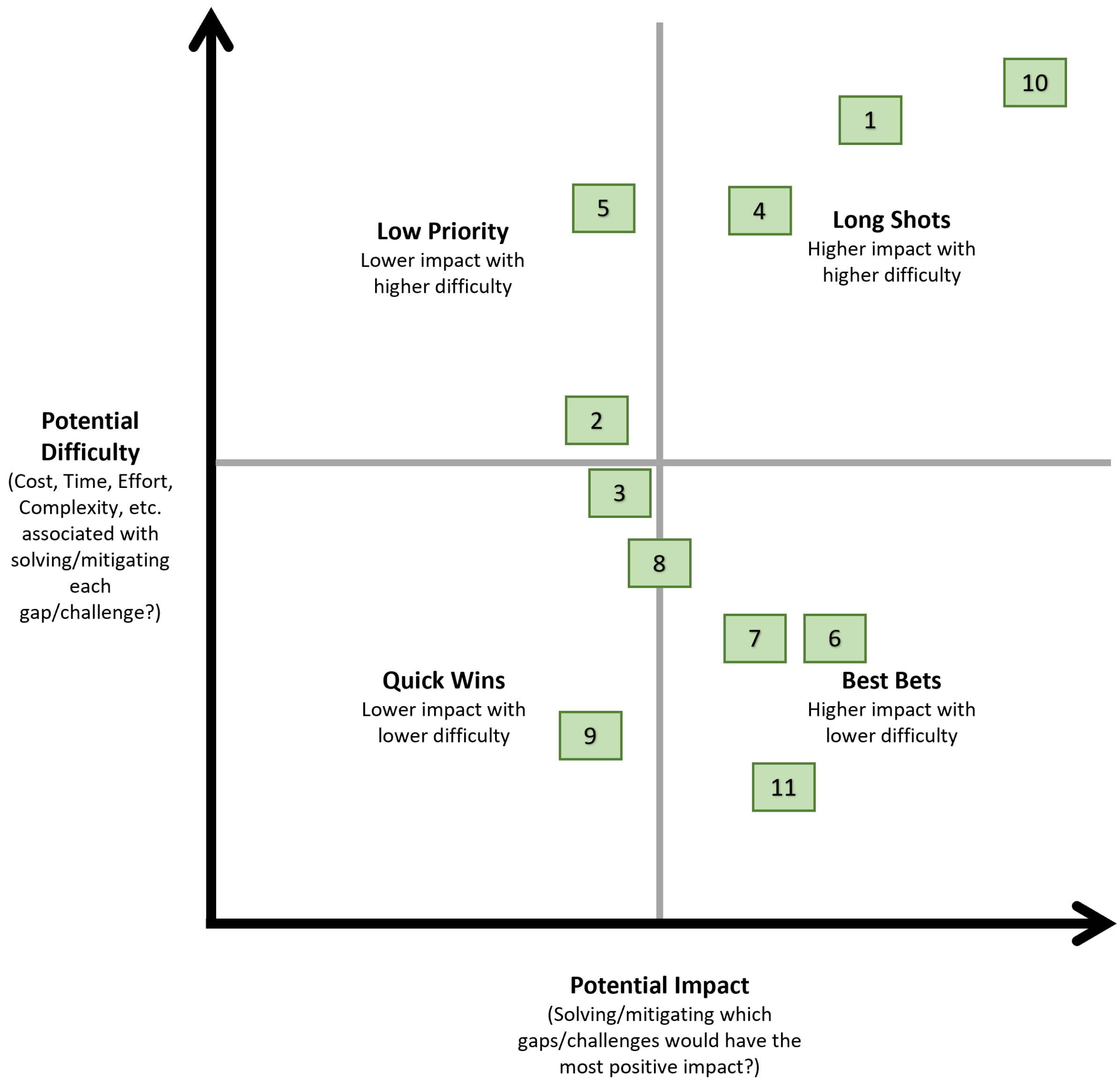
Gap/ Challenge ID	Gap/ Challenge Short Name	Gap/ Challenge Description	Identified in Literature Review and/or Interviews?	Potential Impact of Addressing Gap/ Challenge	Potential Difficulty in Addressing Gap/ Challenge
		cybersecurity, communications, realistic lane changing/merging behavior, etc.)		generation, micro-mobility, shared mobility, traffic signalization, lane changing, and emerging ITS components to better reflect current and future roadway conditions. • Increased use of hybrid and/or multiresolution modeling tools for improved ability to analyze, model, and simulate ITS components at multiple resolutions.	developing, enhancing, and licensing these tools.
5.	Difficulty with properly integrating AI/ML for output interpretation	Difficulty in properly incorporating AI/ML into AMS for ITS tools and producing interpretable outputs	Interviews	• Better guidance on how best to leverage AI/ML in AMS for ITS tools to safeguard against drastic operational performance changes. • More robust, interpretable tools that combine AI/ML, physical, and behavioral models. • More appropriate use and documentation of AI/ML in AMS for ITS tools, leading to increased trust in them and their subsequent use.	• Cost to develop and update best practices for incorporating AI/ML. • Difficulty in increasing the interpretability of deep learning ML techniques due to their “black box” nature. • AI/ML are ever evolving, make it difficult to reach a consensus for how best to apply these techniques to AMS for ITS tools.

Gap/ Challenge ID	Gap/ Challenge Short Name	Gap/ Challenge Description	Identified in Literature Review and/or Interviews?	Potential Impact of Addressing Gap/ Challenge	Potential Difficulty in Addressing Gap/ Challenge
6.	Uncertainty in incorporating emerging ITS data with AMS tools	Uncertainty for how agencies and researchers can/should handle, store, utilize, process, and/or incorporate emerging ITS (big) data with their AMS tools; lack of enough standards and engagement with standards for ITS data	Interviews	• Increased engagement in ITS data standards' development and subsequent adoption. • Better understanding of how to utilize, process, and/or incorporate ITS (big) data with AMS tools. • Increased accuracy and reliability of AMS for ITS tool outputs.	• Cost for developing guidance, use cases, and/or training and updating them as advances are made and new/updated software are created. • Breadth of tools and ITS components used in practice is vast, presenting difficulty in providing support that adequately meet agency/practitioner and researcher needs. • Since emerging ITS components are ever evolving and various standards are not finalized, there exists a lack of consensus for many components, which is difficult to resolve.
7.	Lack of AMS for ITS best practices documentation	Lack of an AMS for ITS best practices clearinghouse	Interviews	• More consistent understanding of best practices for AMS for ITS tool development, calibration, validation, and documentation made available through a one-stop-shop setup.	• Cost to update current guidance and/or develop new best practices and guidance, and making further updates as new enhancements are created. • Cost to create training and/or course to assist researchers in

Gap/ Challenge ID	Gap/ Challenge Short Name	Gap/ Challenge Description	Identified in Literature Review and/or Interviews?	Potential Impact of Addressing Gap/ Challenge	Potential Difficulty in Addressing Gap/ Challenge
				• Development of trusted and verified tools that have a higher likelihood of being adopted in practice.	their tool calibration and validation efforts. • Breadth of tools being developed through and used in research is vast and ever evolving, presenting difficulty in providing relevant best practices that adequately meet researcher needs.
8.	No dedicated open data hub for AMS for ITS data	Lack of an open data hub specifically for AMS for ITS data	Interviews	• A one-stop-shop with open-access cleaned, formatted, and well-documented data that can be used for development, training, calibrating, validating, and testing AMS for ITS tools. • Access to large amounts of a variety of input data that researchers might otherwise not be able to easily obtain. • Enhanced developments of data-driven AMS for ITS tools.	• Cost to collect/generate and document data. • Cost to operate and maintain the data hub as well as provide technical assistance to the system's users. • Potential for overlap in scope with the ITS JPO's Data Program ITS DataHub.
9.	Lack of an open collaboration environment for	Lack of an open, easily accessible connected AMS for ITS tool development	Interviews	• An online and/or cloud-based collaborative open-access tool development environment, similar to and/or building off of Virtual	• Cost to develop, operate, maintain, and continuously enhance such a system and the associated dynamic storage and computational

Gap/ Challenge ID	Gap/ Challenge Short Name	Gap/ Challenge Description	Identified in Literature Review and/or Interviews?	Potential Impact of Addressing Gap/ Challenge	Potential Difficulty in Addressing Gap/ Challenge
	AMS for ITS tool development	environment where multiple researchers at various locations can collaborate and interface with other software		Open Innovation Collaborative Environment for Safety (VOICES). • Faster and more robust AMS for ITS tool collaborative development. • Ability to connect researchers, practitioners, etc. who normally would not work together. • Common datasets, models, and networks can be used as benchmarks. • Community forum for collaboration will accelerate implementation.	components. • Possible reconciliation of licensing and/or copyright issues for any developed tools stemming from such a government-funded resource.
10.	Tool reliability limitations	Tool reliability limitations (e.g., in oversaturated conditions, on low-volume roadways, on facilities larger than specified sizes, credibility issues with constant software versioning and subsequent	Literature: MATSim, BEAM CORE, DTALite, POLARIS, Paramics, MITSimLab, StreetLight Data; and Interviews	• Better ability to document applicable tool use cases based on calibration and compare against validation data. • Enhanced understanding and tracking of reliable tool use as well as gaps that further research could fill.	• Cost to develop and continuously update templates, guidance, and/or training for best practices in documenting tool assumptions, calibration, and validation efforts, etc. • Cost for sponsoring research to fill documented research tool reliability gaps.

Gap/ Challenge ID	Gap/ Challenge Short Name	Gap/ Challenge Description	Identified in Literature Review and/or Interviews?	Potential Impact of Addressing Gap/ Challenge	Potential Difficulty in Addressing Gap/ Challenge
		compatibility issues etc.)			• Hard to compare results of different tools using different inputs. • Significant resources required for benchmarking and quality assurance (QA)/quality control (QC) needs.
11.	Significant hardware and storage requirements	Significant CPU/GPU and storage requirements needed to run AMS tools	Literature: MATSim, BEAM CORE, DynaMIT, CARLA, Vissim, Paramics	• Access to online storage and computational platforms could expand access and use of high fidelity and robust ITS for AMS tools. • Increased AMS for ITS research tool development.	• Cost for providing secure online storage. • Cost for hosting, maintaining, and supporting a secure online computational platform.



Source: ITS JPO

Figure 1. Analysis of Potential Difficulties vs. Impacts for the ITS JPO's AMS for ITS Program to Address the Identified Gaps and Challenges

The qualitative difficulty vs. impact analysis presented in Figure 1 indicates that the ITS JPO's AMS for ITS Program may utilize its resources most effectively by focusing support on the gaps/challenges with higher positive impacts and lower difficulties to address (i.e., "Best Bets" or "Quick Wins"), and are as follows:

- **Potential Best Bets** (higher impact with lower difficulty)
  - **Gap/Challenge 6:** Uncertainty for how agencies and researchers can/should handle, store, utilize, process, and/or incorporate emerging ITS (big) data with their AMS tools; lack of enough standards and engagement with standards for ITS data.
  - **Gap/Challenge 7:** Lack of an AMS for ITS best practices clearinghouse.
  - **Gap/Challenge 8:** Lack of an open data hub specifically for AMS for ITS data.
  - **Gap/Challenge 11:** Significant CPU/GPU and storage requirements needed to run AMS tools.
- **Potential Quick Wins** (lower impact with lower difficulty)
  - **Gap/Challenge 3:** Lack of guidance for how to promote and facilitate adoption of research-developed AMS for ITS tools and methods with state agencies and practitioners.
  - **Gap/Challenge 9:** Lack of an open, easily accessible connected AMS for ITS tool development environment where multiple researchers at various locations can collaborate and interface with other software.

Gaps/challenges that were determined to be highly difficult to address can still provide positive impacts (“Long Shots”, “Low Priority”), however, future benefits will likely require significant financial costs, effort, and/or time to achieve. The following gaps/challenges listed below fall within these categories:

- **Long Shots** (higher impact with higher difficulty)
  - **Gap/Challenge 1:** Lack of available empirical driver behavior, pedestrian, bicyclist, other micro-mobility-specific data and/or processes and measures to consistently validate advanced AMS for ITS tools (e.g., for modeling ITS such as CAVs). Lack of understanding of driver behavioral response to ITS (e.g., DMS, dynamic tolling, managed lanes, CAVs) and corresponding field-collected empirical field-collected data (e.g., raw trajectory open-source data for non-equipped vehicles, CVs, AVs, CAVs, VRUs, and mixed environment traffic).
  - **Gap/Challenge 4:** Tool scope limitations (e.g., facility types, lane designation types, transit modes, micro-mobility modes, shared mobility, realistic collision and/or near-miss incorporation, emerging and enhanced ITS components and strategies, safety analysis, cybersecurity, communications, realistic lane changing/merging behavior, etc.).
  - **Gap/Challenge 10:** Tool reliability limitations (e.g., in oversaturated conditions, on low-volume roadways, on facilities larger than specified sizes, credibility issues with constant software versioning and subsequent compatibility issues etc.).
- **Low Priority** (lower impact with higher difficulty)
  - **Gap/Challenge 2:** Limitations with tool user interface, visualization functionalities, and illustrative capabilities.
  - **Gap/Challenge 5:** Difficulty in properly incorporating AI/ML into AMS for ITS tools and producing interpretable outputs.

6 Conclusions

This chapter summarizes key findings from the conducted literature review that identified AMS for ITS tools developed through and used in research along with the discussions held with a volunteer group of expert stakeholders from state, local, and regional agencies and consultants, vendors/tool developers, and academic researchers who are conducting relevant research. It is important to note that an exhaustive survey of all relevant tools used for research and research entities was not feasible, but this report instead aims to cover a set of tools and entities representative of the state of research for AMS for ITS. Additionally, this chapter denotes the most relevant opportunities for the ITS JPO's AMS for ITS Program to possibly fill and/or mitigate identified gaps and challenges. The findings from this report and corresponding opportunities to address gaps and challenges will be combined with those from the concurrent report that focuses on the State of Practice for AMS for ITS tools. The collective findings from these reports are intended to provide the foundational analysis for the ITS JPO's AMS for ITS Program Plan development.

6.1 Summary of the AMS for ITS Tools Used in Research from the Literature Review and Stakeholder Interviews

Tools that perform analysis, modeling, and/or simulation that include at least one ITS component (e.g., ITS strategy, technology, data) and are used to and/or developed through research within the past three to five years are included in this report. A total of 20 AMS for ITS tools were identified and assessed as part of the literature review. Most of these tools fall within at least one of the seven TAT categories identified by [13], which are sketch planning; travel demand models; analytical/deterministic; traffic optimization; macroscopic simulation; mesoscopic simulation; and microscopic simulation. The category with the highest number of tools is microscopic simulation. Information regarding the following areas was captured for each of the identified AMS for ITS tools: tool description; tool category(ies); primary purpose(s)/objective(s); scope; data inputs/requirements; performance measures; known entities that use/enhance the tool and select research use cases; and a summary of key findings from the review of the tool, including advantages and gaps/challenges in regard to researcher use. For each tool category, except for the "Other" tool category due to the differing natures of the tools, fidelity and/or resolution are discussed. Within the "Other" tool category, fidelity and/or resolution are captured for each tool. Table 24 in Appendix A provides a summary table of the tools. Additionally, interviews were conducted with 20 stakeholders representing 15 organizations ranging from public transportation agencies to consultants to tool developers to academic research institutions, with an emphasis on tools developed through and/or used in research. Many of the tools that researchers (or practitioners, consultants, and/or vendors conducting research) identified as ones they use, develop, and/or enhance are included in the literature. However, some of the tools researchers indicated that they use are in-house and specific to their groups, do not incorporate any ITS components, or are still under development/new and do not yet have publications/documentation that would indicate they are currently part of the state of research.

The following insights regarding the state of research AMS for ITS tools were found based on the literature review and interviews with stakeholders:

- There are a number of tools that are used both in practice and research. In practice, they tend to be utilized as intended, leveraging their default capabilities. In research, these tools may be used as intended to analyze, model, and/or simulate inputs from other research-developed tools or to generate outputs to be further analyzed via other research-developed tools to address research problems. Additionally, in research, these tools' functionalities/capabilities may be extended or enhanced through APIs and SDKs to address research problems.
- A variety of AMS for ITS tools are used in and/or developed through research and most align well with the TAT categories. The majority of the identified tools used for research are high-fidelity microscopic simulation ones that are used for operational, control, design, planning, and evaluation for ITS strategies, applications, and technologies.
- Mobility and environmental impact performance measures are the most prevalent outputs from research AMS for ITS tools, while fewer tools output safety-specific measures. Interviewed researchers noted a need to better model safety impacts and use straightforward, easy to understand, and agreed upon measures to assess all types of objectives.
- Even though less than half of the reviewed tools have MRM capabilities, the interviewed researchers reported that they are performing an increasing amount MRM with an emphasis on real-time hybrid modeling.
- AI/ML techniques and algorithms are becoming more prevalent in AMS for ITS tools used for research for purposes such as enhancing demand and choice modeling, performing vision-based detection, modeling/improving modeling of the movements/behaviors of CAVs, leveraging, cleaning, analyzing, and/or fusing large datasets for improved data-driven transport planning and policymaking, etc. However, researchers noted that these advanced techniques can be misused and difficult to interpret.
- Researchers utilize a mix of historical and/or real-time in-house field collected data, in-house simulator collected/generated data, open-source data (e.g., OpenStreet Map, NPMRDS, state DOT, NGSIM), and/or proprietary data that are purchased or accessed through partnerships (e.g., INRIX, StreetLight Data, Wejo, Veraset, SafeGraph) to develop, train, calibrate, test, validate, enhance, and/or use AMS for ITS tools.

6.2 Potential Opportunities for the AMS for ITS Program to Address Key Gaps and Challenges

Eleven (11) gaps/challenges were identified and consolidated (see Table 23**)** based on the state of research for AMS for ITS tools obtained from the representative, but non-exhaustive literature review and set of researcher stakeholder interviews. A qualitative analysis of these gaps/challenges was conducted with the project team and federal stakeholder AMS for ITS SMEs to help prioritize AMS for ITS Program activities based on positive impact potential that researchers might experience and potential difficulties that would be faced by the ITS JPO's AMS for ITS Program if the Program pursued mitigating/solving them (see Figure 1). This analysis will be used, in conjunction with the analysis from the concurrent State of Practice for AMS for ITS report, to help guide the AMS for ITS Program goals, objectives, and activities. Findings from this report and the qualitative analysis indicate that the AMS for ITS Program may be best positioned to initiate activities to help mitigate/solve the following gaps/challenges with medium to high positive impacts compared to relatively medium to low levels of difficulty that could be faced by the Program:

- **Gap/Challenge 3:** Lack of guidance for how to promote and facilitate adoption of research-developed AMS for ITS tools and methods with state agencies and practitioners.
- **Gap/Challenge 6:** Uncertainty for how agencies and researchers can/should handle, store, utilize, process, and/or incorporate emerging ITS (big) data with their AMS tools; lack of enough standards and engagement with standards for ITS data.
- **Gap/Challenge 7:** Lack of an AMS for ITS best practices clearinghouse.
- **Gap/Challenge 8:** Lack of an open data hub specifically for AMS for ITS data.
- **Gap/Challenge 9:** Lack of an open, easily accessible connected AMS for ITS tool development environment where multiple researchers at various locations can collaborate and interface with other software.
- **Gap/Challenge 11:** Significant CPU/GPU and storage requirements needed to run AMS tools.

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Appendix A. Summary of AMS for ITS Tools Used in Research

Table 24. Summary of AMS for ITS Tools Used in Research

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
Sketch Planning	EVI-X Suite	• Performing analysis and modeling of charging infrastructure deployments considering the demand and existing supply of EVs for planning purposes • Providing charging infrastructure projections based on	• EV charging infrastructure • Output for analyzing emissions modeling/monitoring and providing decision support inputs needed for EV demand management	• Transportation and Land-Use Data • Demographic and Census Data • EV Ownership/Adoption Rate Data • Existing Standard and DCFC Charging Stations	• Energy Delivered Per Charger, Total Energy Delivered (kWh), SOC, Charging Station/Port Utilization, eVMT, etc.	• Assessment of electric vehicle charging infrastructure in Maryland • Estimate for the impacts of depot charging on electricity distribution systems for heavy-duty truck electrification • Assessment to understand the charging flexibility of shared	• EVI-X Suite is one of the initial efforts to analyze EV adoption and quantify/estimate the impacts of EV penetration rates on the national grid • Its support of planning for equitable distribution of standard or fast charging stations • The tool suite has interactive tools that make it easier for analysts to estimate EV impacts • Some of the tools within the EVI-X Suite are currently being develop/refined. As of now, EVI-X Suite does not

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
		daily travel, dynamic charging infrastructure design, energy estimation and site optimization, equitable distribution of charging stations, and other aspects such as fleet electrification analysis				automated electric vehicle fleets • Modeling and analysis of a fast-charging station and evaluation of service quality for electric vehicles	incorporate traffic flow modeling or driver behavior into its analyses • EVI-X Suite relies on a network of other transportation data, tools, and capabilities to complete charging infrastructure analysis
Travel Demand Models	TransCAD	• Forecasting and modeling travel demand of a given area and assigning it to a road network	• Cities, regions, and country-wide travel demand • ITS applications such as emissions modeling, toll lanes, and	• Geometric Data • Forecasts of future population, households, and employment throughout the analysis zones	• Average Traffic Volume, VMT by traveler type, Average Travel Times, Average Speeds,	• Incorporation of AVs in the Traditional Four-Step Model • Assessment of anticipated regional impacts of CAV travel in Austin, TX	• The tool consists of a single platform that is able to perform multiple functions, including model application, model estimation, database support, GIS-based analysis, and graphical/analytical postprocessing, etc. • Its capability to support all major methodologies of

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
		• Transportation network analysis, public transit accessibility measurement, choice modeling (discrete choice, mode choice, route choice), user equilibrium analysis, DTA, and non-motorized travel analysis	dynamic traffic routing	• Information about future transportation networks	Transit Ridership, Transit LOS, Transit Accessibility Measures (access, egress, walk, and transfers to transit), Emissions Per Mile, Total Trips, Total Miles, etc.	• Model for inclusion of innovative scenarios for intra-city freight delivery • Proposed methodology for a tour-based freight model • Model to assess benefits of travel time savings by truck platooning in Korean freeway networks	travel demand modeling methods, including sketch planning methods, four-step demand models, activity-based demand models, and other advanced disaggregate modeling techniques • Its support of various modeling options (e.g., discrete choice models, mode choice models) • Its ability to perform integrated modeling of all modes of transportation including car, HOV, truck, bus, rail, bicycle, and pedestrian movements • Its incorporation of visualizations with dozens of thematic mapping styles and options • TransCAD has U.S. geographic and census demographic data embedded in the tool • Its ability to be integrated with TransModeler to create

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
							a multiresolution model for more comprehensive modeling • Its incorporation of ML algorithms, such as decision trees, that are explainable for population synthesis • Access to TransCAD requires a paid license • Additional skills and training may be needed to make full use of the tool's functionalities. For example, knowledge on GISDK scripting may be required to incorporate custom scenarios such as AV demand modeling
Travel Demand Models	Visum	• Assist transportation agencies and researchers plan for future investments in	• Transportation networks at the city and regional levels • When integrated with microscopic	• Geometric Data • Traffic Flow/ Travel Demand Data	• Average Travel Times, Average Speeds, Delay, Density, VMT, etc.	• Model to evaluate a load balancing mixed freight coordinated assignment system with the inclusion of diesel and	• Its inclusion of a GUI that is easy to use and enables efficient design of network scenarios • Its support of activity-based demand models, which model mobility decisions of individuals instead of groups, in addition to four-

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
		transportation infrastructure and sustainable mobility • Help users understand which operational and infrastructure enhancements yield the best performance	tools such as Vissim, ITS applications at the macroscopic level			electric trucks on realistic road networks aiming for the optimal total combined cost of energy consumption and time • Integrated Visum and Vissim model to evaluate the impacts of complete streets • Model to simulate bicycle traffic in Warsaw, Poland	step trip-based demand modeling • Its incorporation of all standard modes of transportation – drive-alone auto, carpool, public transit, bicycles, pedestrians, and trucks • Its ability to integrate with Vissim for more comprehensive multiresolution modeling and simulation • Additional skills/training may be needed to effectively use the tool • Access to this tool requires a paid license
Mesoscopic Simulation	MATSim	• Simulate primarily large-scale transportation networks, including road networks,	• Link- and network-wide (comprising of local roads, arterials, and	• Network Data • Population Data • Travel Demand Data	• Travel Time, Travel Delay, Speed, Queue Lengths, Capacity Utilization,	• Model to estimate the potential benefits of increased public transit ridership in	• MATSim is an agent-based modeling framework. So rather than just aggregating travelers into groups or averaging their behaviors, this tool allows for a more detailed understanding of the transportation system

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
		public transit systems, and pedestrian and cycling infrastructure • Model travel behavior of individual travelers, considering their preferences, constraints, and decision-making processes • Optimize traffic flow by modeling the interactions of individual travelers with the transportation network,	freeways) analysis • Various types of traffic signals, including fixed-time signals, actuated signals, and adaptive signals • Traffic management strategies, including ITS strategies such as ramp metering and dynamic traffic assignment • Various types of ITS technologies, such as ATIS and AVs	• Public Transport Data (if simulation includes public transport)	Network Accessibility (measure of the ease with which a section/portion of a network can be accessed), Emissions, Energy Consumption, Noise Pollution, etc.	medium sized cities • Agent-based simulation model to evaluate merits of connected corridors and determine future steps • Model to simulate intermodal shared mobility in the San Francisco Bay Area, CA	and the ability to capture complex behaviors and interactions between agents • It is an open-source framework that is available, customizable, and adaptable to a wide range of transportation systems and research questions • It has the ability to simulate large-scale transportation systems with thousands to millions of agents with its scalability. This enables modeling of urban transportation systems and evaluating the impacts of transportation policies and interventions • It has the ability to generate realistic activity schedules for agents, considering factors such as time constraints, mode availability, and activity location, which allows for more accurate modeling of transportation demand that can help identify areas

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
		and adjusting traffic signals, routes, and other factors to improve overall traffic flow					where transportation infrastructure and services may be lacking • MATSim requires significant computational resources and time to run simulations for a large-scale transportation system and/or a large number of agents with detailed activity plans • Users of the tool may experience challenges with ensuring accurate calibration and validation when trying to match the simulation results to real-world data, which can lead to uncertainty in the results and limit the usefulness of the simulation for decision-making • Accuracy of the tool's outputs is highly dependent on the quality and availability of data, which may not be available or

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
							may be prohibitively expensive to obtain • The tool has a highly complex modeling framework that can be difficult for non-transportation modeling experts to use and understand, which can be a barrier to adoption • Additional skills and training may be required to make full use of the tool's functionalities • As an open-source tool, there is limited technical support available to users
Mesoscopic Simulation	BEAM CORE	• Evaluate the impacts various operational and control strategies as well as emerging technologies are anticipated	• Transportation systems at a regional scale including transit (bus and rail) system design, land-use development	• Network Data: • Population Data • Public Transport Data • Survey Data	• GHG Emissions, Energy Consumption Per Mile, VMT, PMT, VHT, Ratio of VMT/VHT, Vehicle Occupancy (both public	• Simulation of the introduction of on-demand, automated, and electric shuttles for last mile connectivity in Santa Clara County, CA	• Its ability to simulate large scale networks • Its ability to model newer forms of transportation such as ride-hailing, micro-mobility, electric vehicles, etc. • BEAM CORE utilizes publicly available data (e.g., OSM, GTFS, etc.)

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
		to impact travelers and the transportation network ahead of deployment • Understand how results from a limited pilot programs will scale to a broader implementation	, and freight demand operations • ITS applications and emerging technologies including AVs, EVs and emissions monitoring, low emissions zone management, dynamic lane management, shared mobility (e.g., ride-hailing, shared scooters, e-bikes, and micro-transit), telecommutin		and private transportation), Freight-Specific Measures, etc.	• Models to help plan for and inform about smart cities • Model to understand plug-in electric vehicle charging demand and develop a framework for behavior energy autonomy mobility	• The tool requires significant computational power and resources • BEACK CORE lacks a graphical interface and requires prior programming experience, which can hinder accessibility • Users of the tool require the tool developers' support to understand the latest capabilities and functionalities, which are constantly updated. However, since BEAM CORE is an open-source tool, there may be limited technical support available to users • Output files require post-processing • Additional skills and training may be required to make full use of the tool's functionalities

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
			g, freight last-mile delivery innovations, and congestion pricing, etc.				
Mesoscopic Simulation	DynaMIT	• Support the operation of ATIS and ATMS at TMCs by optimizing their operations through the provision of real-time predictions	• Historical databases and model coordination efforts for evacuation and rescue operations in real-time emergencies (e.g., natural disasters, etc.) • ITS technologies such as VMS • ITS strategies including alternative traffic signal control	• Travel Demand Data • Real-Time Traffic Flow and Other Exogenous Data • Geometric Data • Traffic Control Data	• Travel Time (mins), Flows (veh/hr), Densities (veh/ln/mi), Queue Length (ft), etc.	• Model for dynamic toll pricing using dynamic traffic assignment system with online calibration • Optimization of transportation systems using an information provision, personalized incentives, and driver cooperation • Real-time data fusion for traffic prediction and	• It is able to handle a variety of real-time scenarios such as for incidents, special events, adverse weather conditions, highway construction activities, fluctuations in demand, etc. • It is able to distinguish between informed and uninformed drivers • DynaMIT has long simulation run times • It is unable to simulate traffic for large scale networks. • DynaMIT requires a paid license to access the tool • Additional skills and training may be required to make full use of tool's capabilities

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
			schemes, ramp metering, and real-time incident management and control			crisis management architecture	
Mesoscopic Simulation	DTALite	• Capture the dynamic decision making of individual travelers given various factors • Test various traffic managemen t and ITS strategies • Analyze formation, propagation, and dissipation of traffic congestion on a	• Various ITS, including signal optimization, ramp metering, dynamic pricing, eco-routing, smart work zones, etc., • Traffic management strategies	• Network Data • Travel Demand Data • ATMS Strategies • Emissions Data	• Time Dependent Link-, Path-, and Network-Level Travel Times, Speed, Density, Volumes, Vehicle Distributions , Vehicle Trajectories, Vehicle Speed/Accel eration Profiles, Fuel Consumptio n,	• Model for an integrated and personalized traveler information and incentive scheme for energy efficient mobility systems • Model for eco-system optimal time-dependent flow assignment in a congested network • Model of a decision support	• It is able to model the dynamic nature of transportation networks, optimal eco-routing/green routing flows that minimize vehicular emissions in a congested network, and optimized ITS and traffic management strategies • It is interoperable with inputs/outputs to/from other tools such as MOVES (emissions model), agent-based models, etc. • Additional skills and training may be required to make full use of the tool's functionalities • As an open-source tool, there is limited technical support available to users

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
		transportation network			Emissions, etc.	system for transport corridors based on dynamic transport flow distribution	• DTALite uses a simplified model to represent signalized intersections (i.e., the traffic signal cycle's effective green times) and does not include all parameters (e.g., offset, coordination, etc.) • The tool has difficulty representing complex traffic control intersections • DTALite can only represent vehicular traffic and no other modes of transportation
Mesoscopic Simulation	POLARIS	• Model the impacts of CAVs, MaaS, EVs and charging infrastructure, freight logistics, as well as system optimization	• Large-scale (city or regional level) • ITS strategies, including emissions modeling, dynamic traffic management and	• Travel Surveys • Census and Employment Data • Transportation Network Geometry • Transit Information	• Average Speed, Density, Flow Rate, Energy Consumption, Travel Time, VMT, etc.	• Simulation model for coordinated transit response planning and operations support for mitigating impacts of hazard emergency events	• It is able to model multimodal metropolitan transportation systems, ITS, and traffic management strategies • The tool is able test the impact of emerging mobility and technologies • POLARIS is able to simulate 10 million agents (i.e., vehicles) in 4-6 hours of model run time

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
		• Test various ITS and traffic management strategies • Activity generation, activity planning (i.e., choice modeling), and multimodal transportation analysis	intersection control, dynamic lane management, and variable speed control	• Vehicle Ownership and Registration • Land Use Data		• Simulation model to evaluate the transportation energy impact of future population scenarios for Detroit, MI • Simulation model to assess travel demand and energy impacts of privately-owned level 4 CAV technologies	• Some of the data coming from SP choice surveys may vary based on geographical location • It is not easily integrable with existing modeling tools due to its use of an agent-based approach, while other tools use approaches such as trip/tour-based approaches, four step modeling, etc. • A license must first be obtained to use this open-source tool
Microscopic Simulation	CARLA	• Facilitate the training, prototyping, and validation of various approaches to automated driving,	• How automated vehicles interact with each other, pedestrians, and transportation infrastructure	• Autonomous Vehicle Data • Traffic Control Data • Roadway Geometry Data • Pedestrian Data	• Percentage of Success, Average Completion, Off Road Intersection, Other Lane Intersection, Vehicle Collisions,	• Simulation platform to evaluate use of a regulations data interface for two selected scenarios: intersection	• CARLA supports the training, prototyping, and validating of autonomous driving solutions, including for both perception and control • It includes co-simulation features, allowing it to be integrated with many other

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
		encompassing both perception and control aspects, specifically the perception algorithms or learning driving policies	(e.g., traffic controls such as signals, signs, markings, etc.) • Surface streets, freeways, and within the general urban driving environment • Passenger vehicles, buses/shuttles • Emerging ITS technologies of AVs and cooperative automated driving (e.g., ramp metering)	• Weather Data	Pedestrian Collisions, General Collisions, etc.	right-turn-on-red and freeway left-lane use • Simulation for assessing online cooperative lane-changing decision-making and trajectory planning model for CAVs • Integrated model with SUMO to mine CAV driving behavior patterns using vehicle data sources and validate the model's results • Model to simulate a	tools such as Vissim and SUMO • The tool can model different weather conditions by configuring the dynamic weather settings, and it can model different sensors such as depth cameras, Radar, Lidar, etc. • Additional skills and training may be required to make full use of the tool's functionalities • As an open-source tool, there is limited technical support available to users • It is not able to model thermal sensors • It is computationally demanding and requires at least a 6GB GPU or preferably a dedicated GPU capable of running Unreal Engine • CARLA requires significant disk space (at least 170 GB) to use, which may

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
						self-driving bus	require investment in additional equipment to accommodate
Microscopic Simulation	Vissim	• Develop and select preferred alternatives that can be used to determine viable novel improvements based on anticipated traffic growth and demand • Traffic impact analysis, transit center design, railroad grade crossing analyses, toll plaza evaluations, bicycle	• Links and networks (comprising of arterials and freeways) analysis • ITS applications, include ramp metering, adaptive signal control, transit signal priority (LRT and bus), traffic signal preemption at (or near) railroad crossing, emergency vehicle preemption, dynamic	• Geometric Data and Analysis Data • Travel Demand Data • Driver and Vehicle Characteristics • Signal Timing Data • Pedestrian Data	• Density (veh/ln/mi), Maximum Queue Length (ft), Microsimulation Delay (sec/veh), Space Mean Speed (mph), Time Mean Speed (mph), Travel Time (sec), v/c Ratio, 95th Percentile Queue Length (ft), O-D Pair Results, Pedestrian Analysis Results (Maximum/ Minimum	• Model to simulate and evaluate automated vehicles • Model to investigate the effects of major key parameters on CO_2 emissions • Model for a heuristic adaptive traffic control algorithm for signalized intersection • Simulation model to estimate the effects of boarding conditions on bus dwell time	• Its ability to simulate different road user classes such as buses, trucks, pedestrians, and bicyclists • Its incorporation of CAV features, including communications and cooperation among vehicles • Vissim is a high-fidelity multi-resolution software tool • Access to Vissim requires a paid license • Vissim has been noted as requiring more time to code input data than other traffic analysis tools; however, microscopic simulation tools all tend to require more time to code inputs than mesoscopic and macroscopic simulation tools

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
		analyses, pedestrian analyses, and ITS assessments	speed control, dynamic lane assignment, and changeable message signs		Number of Pedestrians, Density, Speed, Travel Time, Delay, etc.), Emissions, Fuel Consumption, etc.	and schedule adherence for passengers with mobility limitations	
Microscopic Simulation	CORSIM	• Replicate the spatial and temporal effects of congestion, model interactions between freeways and urban streets, and perform route assignments using DTA • Model interruptions to traffic flow	• Vehicle and driver behavior as well traffic control systems on links and networks • ITS applications including ramp metering, adaptive signal control, transit signal priority, transit signal	• Geometric Data • Traffic Control Data • Traffic Flow/Travel Demand Data • Driver and Vehicle Characteristics • Pedestrian Data	• VMT, VHT, Average Delay (seconds), Density (vehicles/mile), Vehicle Throughput (vehicles/hour), Average Speed (km/hour), LOS, Average Travel Time (seconds or minutes), Bus Delay Per Vehicle	• Traffic operational analysis for different design alternatives along I-35 in Austin, TX • Examination of the impacts of speed harmonization on I-394 in Minnesota	• Its ability to accommodate time-varying demand, simulate work zone behavior, bus operations, and various ITS • Its ability to support both 2D and 3D visualizations • CORSIM does not model toll booths and weigh stations, two-way left turn lanes, roundabouts, U-turns, or light rail • The tool is considered one-dimensional in the sense that vehicles do not adjust their speeds based on vehicles in adjacent lanes

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
		• Analyze active traffic management strategies for arterials and freeways	preemption at (or near) railroad crossings, emergency vehicle preemption, incident detection and management, managed lanes such as HOV and HOT lanes, market penetration of CAVs with some degree of connectivity, etc.		(seconds/vehicle), Fuel Consumption (gallons), Pollutant Emission (kilograms/ mile-hour), etc.		• Access to CORSIM requires a paid license and the tool may require additional training or skills to effectively use it
Microscopic Simulation	TransModeler	• Compare impacts of operational strategies and design alternatives on a wide	• Links, networks, urban areas, counties, and regions • ITS strategies	• Geometric Data • Signal Timing Data	• VMT, VHT, Average Delay (seconds), Density (vehicles/mile), Vehicle	• Model to examine corridor-based tolling strategies for Virginia's	• It has multiresolution hybrid simulation capabilities in which high-fidelity microscopic simulation can be intermixed with mesoscopic simulation

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
		variety of road networks • Evaluate the impacts of future planning scenarios through integration with TransCAD	and technologies including active traffic management, reversible lanes, hard shoulder running, speed harmonization, adaptive ramp metering, variable speed limits, electronic toll collection, managed lanes, signal preemption, transit signal priority, actuated signal control, CAVs, etc.	• Traffic Flow/Travel Demand Data • Driver and Vehicle Characteristics • Pedestrian Data	Throughput (vehicles/hour), Average Speed (km/hour), Average Stops, Average Travel Time (seconds or minutes), Bus Delay Per Vehicle (seconds/vehicle), etc.	express toll lanes • Integrated model with TransCAD to estimate the time-dependent evacuation behavior of households facing an oncoming hurricane • Evaluation of CAVs and ride-hailing by integrating TransModeler with an activity-based model • Simulation model to test congestion mitigation strategies and evacuation scenarios in	• TransModeler is a GIS-based tool, which makes it simple to automatically load map layers and aerial imagery from Google Earth, Google Maps, OpenStreetMap, USGS Topographic Maps into the tool • Its ability to be integrated with trip-based and activity-based transportation planning models • The tool is integrated with HCS, which enables it to report simulation-based LOS metrics • Its ability to integrate with the travel demand forecasting tool TransCAD • The tool has built-in 3D visualization through Unity 3D Viewer • Outputs and MOEs from TransModeler usually require post-processing and

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
						Virginia Beach, VA	formatting to be usable or interpretable • The tool is sensitive to path setups; if the path where the folder is stored on a machine is changed, or any component is renamed, the tool will require users to relink all the components to the project again (e.g., O-D matrices, turning movement tables, signal files, etc.), which can be time consuming especially if the work is done on different machines • There is limited access to electronic tool user manuals since they are accessible only when running the tool • Access to TransModeler requires a paid license and the tool may require additional training or skills to effectively use it
Microscopic Simulation	Paramics	• Model and simulate individual	• Links, networks, urban areas,	• Geometric Data	• VMT, VHT, Average Delay	• Simulation model to assess the	• Its ability to perform large-scale microscopic simulations with detailed

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
		components of the traffic stream for planning and analysis purposes • Model and simulate numerous traffic operations scenarios including traffic congestion, traffic signal control analysis, public transport operations, event planning, etc. • Assess pedestrians' and bicyclists' safety and	and entire cities at the microscopic level • Public transportation • ITS strategies and components such as ramp metering, reversible lanes, dynamic lane management, hard shoulder running, active traffic management strategies, eco-speed harmonization, connected and	• Traffic Control Data • Traffic Flow/Travel Demand Data • Driver and Vehicle Characteristics • Pedestrian Data	(seconds), Density (vehicles/km), Vehicle Throughput (vehicles/hour), Queue Length, Average Speed (km/hour), Average Stops, (seconds or minutes), Total Time Stopped for Public Transit (seconds or minutes), Passengers Boarding/Alighting, etc.	impact of traffic management on black carbon emissions • Assessment of the potential mobility, environmental, and safety impacts of connected vehicles • Assessment of the potential accessibility, health, and financial impacts of the Dundee, Scotland LEZ	driving behavior such as acceleration/ deceleration, lane-changing, and car-following at a time resolution of 0.1 sec • Its ability to test, simulate, and analyze the impact of various emerging ITS technologies (e.g., CVs) and traffic management strategies • Its ability to incorporate pedestrians and bicyclists in modeling and visualization • It has built-in 3D visualization • Simulations are potentially computationally intensive and require significant resources and time, especially for large-scale networks. Additionally, Paramics has potentially time- and data-intense model development and calibration, depending on the size of network and complexity of scenario

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
		model and simulate infrastructure design alternatives as well as perform environmental assessments	automated vehicles, etc.				• It does not have the capability to output signal coordination timing • Outputs and MOEs from Paramics may require post-processing to be useable/ interpretable • Access to the tool requires a paid license, and the tool may require additional training or skills to effectively use it
Microscopic Simulation	MITSIMLab	• Evaluation of impacts of alternative traffic management system designs at the operational level and assisting in subsequent refinement	• Systems, links, and segments • ITS applications, include ramp metering, freeway mainline control, dynamic lane control signs, variable speed limit signs, portal signals at	• Travel Demand Data • Traffic Control Data • Transit Network, Schedule Design and Fleet Assignment • Traffic Flow Data	• Traffic-related: Flow (veh/hr), Speed (mph), Density (veh/ln/mi), Queue Lengths (ft), Delay (sec), Travel Time (min) • Transit system-related: Total Passenger	• Simulation framework for crisis management • Model for cooperative lane-changing and forced merging behavior	• The tool enables detailed representations of routes and schedules, which allow transit and traffic operations in the simulated network to be sensitive to the variations in the route and schedule inputs • MITSIMLab provides real-time sensor data that mimics the surveillance capacities of the traffic management systems in an ITS environment

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
			tunnel entrances, intersection controls, variable message signs, in-vehicle route guidance etc.		Travel Times (min), Number of Late Trips, Driver Overtime, Average Running Speed (mph), Travel Time Distribution, Average Dwell Times (min), Waiting Times (min), Travel Times (min), etc.		• Its ability to model a wide range of traffic management system designs • Its lack of on-going updates by the original tool developer • The tool requires detailed data at an individual user level, including trajectories at high time resolution, for model calibration • Its lack of a functionality extension API as well as 3D visualization • Additional skills and training may be required to make full use of the tool's functionalities • As an open-source tool, there is limited technical support available to users
Microscopic Simulation	INTEGRATION	• Model and simulate dynamic traffic phenomena, such as	• Light duty cars, light duty trucks, heavy duty trucks, buses, etc.	• Roadway/Link Traffic Flow Data • Traffic Control Data	• Link Travel Times (seconds or minutes), Vehicle Delay	• Estimation of the effects of reduced traffic demand vehicle delays, fuel	• It combines traffic assignment with microscopic simulation, which makes it possible to model and simulate pre-trip

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
		shock waves, gap acceptance, weaving as well as the impacts of traffic management strategies and the impacts of ITS applications on the transportation system • Model energy, emissions, and crash risks	• Freeways and arterials, including both signalized and unsignalized intersections • ITS applications, including eco-lanes, speed harmonization and dynamic speed limits, ramp metering, tolling and HOV lanes, adaptive traffic signal optimization, etc.	• Travel Demand Data • Incidents or Lane Blockages (if incidents are being modeled)	(seconds or minutes), Number of Vehicle Stops, Vehicle Fuel Consumption (liters), Vehicle Emissions (grams), Crash Rate and Severity, etc.	consumption, and emission levels • Simulation of a new logarithmic delay model to compute optimum cycle length that considers vehicle delay, fuel consumption, and tailpipe emissions • Evaluation of vehicle performance in terms of fuel consumption at signalized intersections	and enroute driver decisions • It is able to model and simulate large scale networks of up to 10,000 links and 500,000 vehicle departures as well as vehicle energy and emissions • It is able to compute 14 different crash risks, the level of vehicle damage, and passenger injury severity • Access to the tool requires a paid license • It is not able to model pedestrians and their interactions with vehicles on arterials • Additional skills and training may be required to make full use of the tool's functionalities
Microscopic Simulation	SUMO	• Assessing operational strategies as	• Links and large networks	• Geometric Data	• Vehicle Throughput (vehicles/ho	• Simulation model to evaluate	• The tool is open-source and does not require a paid license to access

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
		part of planning by simulating vehicles at the microscopic level • Simulating vehicular communications (i.e., V2X communications)	• ITS applications and technologies, including adaptive signal control, variable speed limits, speed harmonization, hard shoulder running, CAVs, etc.	• Traffic Control Data • Traffic Flow/Travel Demand Data • Driver and Vehicle Characteristics • Pedestrian Data	ur), Average Speed (km/hour), Average Stops, Average Travel Time (seconds or minutes), Density (vehicles/km), Occupancy (%), Average Delay (seconds), etc.	speed harmonization and merge control using CAVs on a highway with lane closure • Assessment of the impacts of a gap acceptance behavior model for a stop-controlled intersection in New Jersey • Model integrated with a VANET simulator built on top of a communication network (OMNET++) to simulate and evaluate the performance of multimodal	• Its ability to model large-scale microscopic simulations • Its ability to model and simulate multiple ITS applications (e.g., connected vehicle applications) • Its compatibility with external software such as Vissim, Visum, MATSim, and others • Usage of SUMO requires prior knowledge of Python, C++, or command line programming as well as the ability to process XML files for initial setup and implementation • Its ability for users of the tool/researchers to extend the tool's capabilities through APIs • It only supports 2D visualization • Since it is an open-source tool, there is limited

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
						adaptive traffic signal control	technical support available to users
Microscopic Simulation	Aimsun	• Transportation policy • Transportation planning • Multimodal transportation analysis • Mobility analytics • Real-time transportation management and predictive analytics • Demand modeling • Estimating the impact of emerging mobility technologies	• Multiple scale levels including the link and network level (comprising of arterials and freeways), urban area level, and regional levels • ITS applications such as ramp metering, adaptive signal control, transit signal priority (LRT and bus), traffic signal preemption at (or near)	• Geometric Data • Signal Timing Data • Traffic Flow/Travel Demand Data • Driver and Vehicle Characteristics • Pedestrian Data	• Average Delay (seconds/mile), Density (vehicles/mile), Flow (vehicles/hour), Average Speed (mph), Mean Harmonic Speed (mph), Average Travel Time (seconds or minutes), Mean Queue Length (number of vehicles), Maximum Queue Length, Total Number of Stops, Fuel	• Model for pedestrian traffic simulation • Simulation model to represent and test a CRM control system's effects on a congested freeway (SR-99N in Sacramento, CA) with multiple vehicle classes • Model for self-learning eco-speed control utilizing a machine learning approach	• Its ability to model and simulate at microscopic, mesoscopic, and macroscopic levels • Its ability to perform multiresolution hybrid modeling such as for hybrid meso-micro and hybrid macro-meso scenarios • Its capabilities can be extended through multiple means, including the tool's API • Its ability to integrate its predictive capabilities with real-time traffic management • Its ability to provide decision support for transportation planning and policymaking • Its ability to discover, forecast, and deploy optimal ITS and traffic management strategies for ICM

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
		• Energy and emissions modeling • Cost-benefit analysis of ITS technologies /strategies	railroad crossings, emergency vehicle preemption, dynamic speed control, dynamic lane assignment, and changeable message signs • ITS technologies such as EVs, AVs, and CVs		Consumption (liters), Pollutant Emission (kilograms), etc.	• Model to simulate an autonomous taxi-system in Munich, Germany	• It has an interface with built-in visualization options as well as the ability to integrate with other tools • Access to Aimsun requires a paid license and the tool may require additional training or skills to effectively use it
Microscopic Simulation	Unity 3D	• Analyze traffic flow and test different traffic management and ITS strategies in a realistic and	• Links and networks • ITS applications and technologies including AVs, V2I communication, V2V	• OpenStreetMap Data • Vehicle Models Characteristics • Traffic Control Systems • Driver Behavior	• Queue Lengths (ft) at intersection and bottlenecks, Average Speeds, Flow (veh/hr),	• Simulation for autonomous motorway traffic applied to help build motorway emergency corridors • Simulation to investigate the	• The tool has a limited capability free version available to users • The tool is a physics-based simulation tool that may be able to simulate vehicle maneuvers more accurately than purely traffic flow

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
		interactive virtual environment • 3D visualization of models as well as the creation of digital twins of environments and real objects such as vehicles and sensors	communication, and I2I communication	• Weather Conditions	Wait Times (min), etc.	impacts of safe distance on traffic flow • Simulation integrated with SUMO to evaluate V2X communication-based systems • Simulation that leverages digital twin and game-engine concepts to evaluate traffic and output effective visualizations	theory-based tools (e.g., car-following) • The tool has a large amount of available documentation and online support • Unity 3D has a wide variety of available libraries and assets to develop models • It is primarily designed for game development, lacking many traffic-specific features found in dedicated traffic simulation engines. There is also limited understanding of its general traffic-specific modeling and simulation capabilities and potential areas of improvement • Its lack of ability for estimating some traffic-specific performance measures, such as intersection delay or traffic v/c ratio • Full access to Unity 3D requires a paid license, and the tool may require

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
							additional training or skills to effectively use it
Other	Autonomie	• Predict and analyze fuel efficiency and cost • Estimate the energy, performance, and cost impact of advanced vehicle and powertrain technologies	• Powertrain components for different vehicle requirements • Vehicle energy • Emerging ITS vehicle technologies, including AVs	• Vehicle Routing and Trajectory Data • Vehicle Parameters and Specifications • Market Penetration Rates of Vehicle Classes	• Energy Consumption, Emissions, and Battery SOC	• Model to simulate energy consumption and cost reduction of future light-duty vehicles through advanced vehicle technologies anticipated through 2050 • Modal-based approach for estimating electric vehicle energy consumption in transportation networks • Future battery material demand	• Its ability to model the fuel efficiency and cost savings impacts of alternative fuel technologies at various market penetration rates • It is able to analyze fuel consumption and estimate emissions for more than 100 vehicle models ranging from light-duty to battery cell EVs • Acquiring required input data such as detailed vehicle parameters and specifications can be difficult • The tool requires continuous updates to incorporate the latest technological advancements in automotive sector (e.g., new technologies, connectivity, advanced

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
						analysis based on U.S. DOE R&D targets	sensors, novel control strategies) • Since it is an open-source tool, there is limited technical support available to users
Other	StreetLight Data	• Corridor planning, first and last mile studies, congestion studies, transportation demand management, bike and pedestrian studies, freight studies, and greenhouse gas emissions studies • Impact studies, detour and route	• Variety of transportation facilities (ranging from isolated intersections to large transportation networks) • ITS applications such as ramp metering, variable speed limits, and smart work zone operations	• Zone Data • Data Analysis Time Periods	• Trip Attributes including Average Speed (mph), Travel Time (min), Distance (mi), VMT • Traveler Attributes including Trip Purpose and Census Demographics (e.g., household income, race, education of head of	• Exploration of crowdsourced monitoring data for safety • Assessment of the impacts of increased adverse weather events on freight movement • Assessment of energy use, emissions, grid integration, and cost impacts for private vehicles compared to	• Its ability to provides data and metrics for several transportation modes including cars, trucks, buses, rail, bicyclists, and pedestrians • It is a self-serve web platform, which allows analysts to access, analyze, and visualize data for a wide range of transportation facilities • The tool provides a quicker way to access traffic data compared to other methods that require installing software and possibly field equipment • It has been shown to have significant overestimation bias for low-volume

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
		planning, and multimodal planning			household, and family status) • O-D Data for Pedestrian Metrics, Bike Metrics and Vehicular Metrics, as well as AADT	shared vehicles, and automated electric vehicles for personal mobility	roadways through validation studies • It relies heavily on the data points sampled from smartphone applications and GPS-enabled devices, which may be subject to potential bias and coverage issues • Access to StreetLight Data requires a paid subscription license, and the tool may require additional training and skills to effectively use it

Appendix B. Stakeholder Discussion Topics

Below are one full set of interview questions asked during interviews with the researcher stakeholders and two research-specific subsets of questions asked during the interviews with practitioner and vendor stakeholders, respectively, to solicit inputs on the state of research for AMS for ITS tools and identify gaps and challenges. Researchers in this context include individuals who conduct research through academic or national laboratory entities. Practitioners include individuals who either work for regional, state, and/or local transportation agencies directly or are hired consultants working for or on behalf of one of these agencies and use AMS for ITS tools. Tool developers are individuals from companies who develop, maintain, upgrade, and provide technical support to users of various AMS for ITS tools. There are similarities between the various sets of questions, but differences exist that are specific to the stakeholder groups.

Researcher Interview Questions

Short Answer Questions

1) What, if any, research activities are you currently utilizing AMS to perform? (Including any of the following):
   a) Impact of emerging mobility and technologies including ITS
   b) Microscopic/mesoscopic/macroscopic simulation
   c) Transportation network and system optimization
   d) Multimodal transportation planning
   e) Activity- and agent-based modeling
   f) Micro-mobility modeling and analysis
   g) Energy and emissions analysis
   h) Traffic safety analysis
   i) Others
2) What tools do you (or your department/organization) typically use for AMS research?
3) Have you (or your department/organization) enhanced any existing tool(s) or developed a new tool to support AMS research? If yes:
   a) What was the focus of the research?
   b) What is the name of the enhanced or new AMS tool?
   c) What is the scale or resolution of the enhanced or new AMS tool?
   d) What are the new features or capabilities of the enhanced or new AMS tool?
4) Have you (or your department/organization) conducted AMS research that involved the following? If yes, explain further.

   a) Multiresolution modeling (MRM)
   b) Activity-based modeling
   c) Agent-based modeling
   d) Data analytics
   e) Artificial intelligence/Machine Learning
   f) Others

5) What are the typical performance measures utilized for evaluation in your AMS research activities? Are these measures directly reported from the AMS tool(s) or are they indirectly generated?
6) What type of data do you use for model calibration and validation in AMS research?
7) How do you collect the input data for AMS for ITS-supported research? Is there any open-source data that your agency utilizes for AMS research? Are there any data sources or data types that are currently not being used that could be useful?

More Elaborate/Open Ended Questions

1) What are the existing gaps and barriers in the use of AMS tools for research that you think should be highlighted? Are there any particular areas or aspects of AMS tools that you feel are currently under-researched or under-developed?
2) What is something you would like to improve about current AMS tool(s) in research and/or practice? Are there any specific capabilities and functionalities that you think should be added to AMS tools for effective evaluation?
3) When you are interested in learning more about AMS tools or are seeking technical support, what resources do you turn to first?
4) Are there any materials (i.e., technical reports, presentations, research articles, etc.), either publicly available or in-house, that you think we should review as part of this effort, and you can share with us?
5) How do you foresee AMS tools evolving in the coming years, and can you share any new developments or emerging trends in AMS for ITS tools that you find promising or noteworthy?

Research-Specific Practitioner Interview Questions

More Elaborate/Open-Ended Questions

1) What are the key limitations of the AMS tools currently used by your agency?
   a) Are there specific use cases that your current AMS for ITS tools cannot accommodate but would fill a current AMS gap?
   b) Does your agency facilitate, collaborate on, or conduct research to enhance current AMS tools or develop new ones?
2) Are there any specific features or functionalities that you would like to see in new AMS tools or through updated versions of current tools?

3) What, if any, barriers exist to further adopting more advanced AMS for ITS tools (i.e., data availability, license costs, workforce/training, etc.)?

Research-Specific Tool Developer Interview Questions

Short Answer Questions

2) What are the key use cases of your AMS tool(s)? Are these use cases for practice and/or research?
4) Do you have any existing or planned AMS tools that incorporate/use any of the following?
   a) Data analytics
   b) Artificial intelligence/Machine Learning
5) What type of data do you use for model calibration and validation when building new functionalities for existing tools or completely new AMS tools?
   a) How do you collect the input data?
   b) Is there any open-source data that your organization utilizes for AMS research?
   c) Are there any data sources or data types that are currently not being used that could be useful?
6) Is your organization enhancing any existing tools or developing new algorithms/approaches/methodologies to support AMS research? If yes,
   a) What is the scale/resolution of the enhancements or developments (e.g., micro, meso, macro)?
   b) What are the new features/capabilities of the enhancements or developments?

More Elaborate/Open Ended Questions

1) What are the existing gaps and barriers in the use of AMS for ITS tools for practice and/or research that you think should be highlighted?
   a) Are there any particular areas or aspects of AMS tools that you feel are currently under-researched, under-developed, or are key areas for improvement?
   b) Are there any specific capabilities and functionalities that you think should be added to AMS tools to enable more effective evaluation?
   c) What are the barriers to the adoption and/or development of more advanced AMS tools?
2) Are there any materials (e.g., technical reports, presentations, research articles), either publicly available or in-house, that you think we should review as part of this effort, and you can share with us?
3) How do you foresee AMS tools evolving in the coming years, and what do you think will be the most important developments in this field?
   a) Can you share any new developments or emerging trends in AMS tools that you find promising or noteworthy?

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