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

AMS for ITS State of Practice

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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 practice for AMS for ITS tools. The AMS for ITS Program seeks to capture the state of practice for AMS for ITS tool use that is representative of state, local, and regional agencies nationwide, with the understanding that a fully exhaustive survey of the community is not feasible. A literature review as well as discussions with a volunteer group of expert stakeholders on AMS for ITS tools used in practice 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, including the advantages of the currently used tools and gaps/challenges practitioners may encounter when applying the tools. It is important to understand the practical needs to support traffic analysis tools (TAT) and other AMS for ITS tool strategies and projects. For example, the 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.

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Executive Summary

The purpose of this document is to summarize the state of practice for AMS for ITS tools 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 AMS for ITS Program seeks to capture the state of practice for AMS for ITS tool use that is a representative snapshot of state, local, and regional agencies nationwide, with the understanding that a fully exhaustive survey of the community is not feasible. A literature review as well as discussions with a volunteer group of expert stakeholders on AMS for ITS tools used in practice were conducted and the identified tools have been categorized and documented in this report. Furthermore, this report captures a summary of key findings for each tool, including the advantages of the currently used AMS for ITS tools and gaps/challenges practitioners may encounter when applying the tools. It is important to understand the practical needs to support traffic analysis tools (TAT) and other AMS for ITS tool strategies and projects. For example, the 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 practice 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 as well as vendors who are practitioners and tool developers 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 are identified. Additionally, a qualitative assessment of the potential positive impacts that may be experienced by the state of practice 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 Practice

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 typical practice were included in this report. A total of 22 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/outputs; known entities that use the tool and select use cases; and a summary of key findings from the review of the tool, including advantages and gaps/challenges in regard to practitioner 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 12 stakeholders representing 8 organizations ranging from public transportation agencies to consultants to tool developers. Most tools that the practitioners 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 have not yet been adopted more prevalently in practice.

The following insights regarding AMS for ITS tools typically used in practice were found based on the literature review and discussions with interviewed stakeholders:

- There exist a variety of AMS for ITS tools used in practice for different purposes with varying levels of fidelity and resolution. Most of these tools align well with the TAT categories and most are used for operational, planning, design, and evaluation purposes.
- Mobility and environmental impact performance measures are the most prevalent outputs from AMS for ITS tools. Safety measures were largely absent from both stakeholder discussions as well as the literature review.
- While the capabilities of many tools can be extended using Application Programming Interfaces (APIs) and Software Development Kits (SDKs), there is limited use of tools in practice that employ state of the art analytical and artificial intelligence (AI)/ machine learning (ML) functionalities due to the lack of maturity/validated trustworthiness and in-practice applications as well as the black-box nature of the most advanced algorithms. Additionally, AI/ML-derived statistical models are not uncommon to represent traffic dynamics and some physical phenomena for control purposes, but these models are almost always trained offline and are not updated with real-time data.
- While there are some uses of multiresolution modeling (MRM) tools in practice, their use as well as the adoption of newer, possibly improved AMS for ITS tools by practitioners appears to be hindered by several key factors:
  - Funding and return on investment (ROI) methods to help present a business case in support of funding.
  - Either lack of required data amount and/or types, or lack of ability to process/understand an overabundance of collected data.
  - Guidance with accompanying training and in-practice use cases.
  - Uncertainty in how to apply research to practice.

- Only a few AMS for ITS tools typically used in practice have real-time/rolling horizon predictive capabilities as most are used for offline planning purposes. However, there are several tools that have recently been released or are under development that are anticipated to have these capabilities.
- Proprietary data (e.g., from INRIX, Wejo, Waze, StreetLight, TomTom) are being purchased or obtained through data sharing agreements by more and more agencies to supplement internal agency collected data to help support AMS for ITS activities.

Key Findings

Fifteen (15) gaps/challenges were identified and consolidated based on the state of practice for AMS for ITS tools obtained from the representative but non-exhaustive literature review; and set of practitioner stakeholder interviews. A qualitative analysis of these gaps/challenges was conducted in terms of the potential positive impact practitioners 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 findings from the complementary State of Research 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 1**: Tool license/subscription cost.
- **Gap/Challenge 2**: Extensive programming/ coding/ tool software workforce training/ development required for standard and/or advanced tool use.
- **Gap/Challenge 4**: Lack of ROI analysis and/or guidance for how and when AMS for ITS tools allow for improved practitioner capabilities and support for the various costs associated with investing in new tools.
- **Gap/Challenge 5**: Tool outputs and measures of effectiveness (MOE) may require post-processing for usability.
- **Gap/Challenge 6**: Significant input data amount requirements.
- **Gap/Challenge 7**: Significant CPU/GPU and storage requirements needed to run AMS tools.
- **Gap/Challenge 13**: 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 15**: Gap in transferring knowledge to practitioners to promote adoption of new methods and approaches. Practitioners often do not have the means or examples to be able to apply and/or know when to apply the most robust AMS for ITS research tools to consistent real-world scenarios/use cases. Lack of guidance for how to promote and facilitate adoption of research-developed AMS for ITS tools and methods with state agencies and practitioners.

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, 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 United States Department of Transportation (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 a 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 Joint Program Office (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 practice 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 practical 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 practice of AMS for ITS tool use that is representative of state, local, and regional agencies nationwide, knowing that an exhaustive survey of the 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 Research report, titled "Analysis, Modeling, and Simulation (AMS) for Intelligent Transportation Systems (ITS) State of Research", which complements this State of Practice report. Although both reports focus on AMS for ITS tools, the State of Research report's scope is limited to AMS for ITS tools used and/or developed by researchers for exploratory, investigative, and developmental work.

1.3 Document Scope

The scope of this document is limited to the practical use of AMS for ITS tools by states, localities, and regional agencies/organizations. 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 practice 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, and vendors who are practitioners and tool developers 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, 15 key gaps and challenges were identified. These gaps and challenges were then qualitatively assessed using an analysis of the potential impacts 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 Practice 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 Practice** – summarizes AMS for ITS tools used in practice 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 Practice** – summarizes the gaps and challenges in AMS for ITS tools used in practice 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 used in practice.
- **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 used typically in practice.
- **Appendix B** – presents the topics/questions discussed with the interviewed 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 technical, institutional/policy, and/or software development processes and assesses the ability of implementing a subsequent contracted 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.
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].
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.
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
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.
Resolution	Resolution is the level of detail that the tool incorporates to represent the real-world.

Term	Definition
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
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
ATDM	Active Transportation and Demand Management
ATSPM	Automated Traffic Signal Performance Measures
AV	Automated Vehicle
BRT	Bus Rapid Transit
Caltrans	California Department of Transportation
CAV	Connected and Automated Vehicle
CCTV	Closed-Circuit Television

Acronym	Definition
CHART	Coordinated Highways Action Response Team
CMM	Capability Maturity Model
CPU	Central Processing Unit
CV	Connected Vehicle
DDI	Diverging Diamond Interchange
DLT	Displaced Left Turn
DSRC	Dedicated Short Range Communications
DTA	Dynamic Traffic Assignment
DYNASMART	DYnamic Network Assignment-Simulation Model for Advanced Road Telematics
DynusT	Dynamic Urban Systems for Transportation
EPA	Environmental Protection Agency
EV	Electrical Vehicle
FHWA	Federal Highway Administration
FREEVAL	FREeway EVALuation
ft	Feet
GIS	Geographic Information System
GISDK	GIS Developer's Kit
GPS	Global Positioning System
GPU	Graphics Processing Unit
GUI	Graphical User Interface
HCM	Highway Capacity Manual
HCS	Highway Capacity Software
HOT	High Occupancy Toll
HOV	High Occupancy Vehicle
hr	Hour
ICM	Integrated Corridor Management
ICMS	Integrated Corridor Management System
ICT	Information and Communications-based Technologies
ICU	Intersection Capacity Utilization
IHSDM	Interactive Highway Safety Design Model
IOO	Infrastructure Owners and Operators
ISATe	Interchange Safety Analysis Tool Enhanced

Acronym	Definition
ITS	Intelligent Transportation Systems
JPO	Joint Program Office
km	Kilometer
KNN	K-Nearest Neighbor
LBS	Location-Based Services
LOS	Level of Service
LRT	Light Rail Transit
LSTM	Long Short-Term Memory
MaaS	Mobility as a Service
mi	Mile
min	Minute
ML	Machine Learning
MOE	Measure of Effectiveness
MOVES	Motor Vehicle Emissions Simulator
mph	Miles Per Hour
MPO	Metropolitan Planning Organization
MRM	Multiresolution Modeling
MTM	Manhattan Traffic Model
MUT	Median U-Turn
N_2O	Nitrous Oxide
NPMRDS	National Performance Management Research Data Set
NYSDOT	New York State Department of Transportation
O-D	Origin-Destination
ODOT	Ohio Department of Transportation
OSM	OpenStreetMap
p-miles	Passenger Miles
pc/mi/ln	Passenger Cars Per Mile Per Lane
PeMS	Performance Measurement System
PHF	Peak Hour Factor
RCUT	Restricted Crossing U-Turn
ROI	Return on Investment
SAFE	Safer Affordable Fuel-Efficient

Acronym	Definition
SANDAG	San Diego Association of Governments
SDK	Software Development Kit
sec	Second
sec/veh	Seconds Per Vehicle
SME	Subject Matter Expert
SO_2	Sulfur Dioxide
SOP	Standard Operating Procedure
SOV	Single Occupant Vehicle
SPUI	Single-Point Urban Interchange
SSAM	Surrogate Safety Assessment Model
SST	Software Selection Tool
SUMO	Simulation of Urban Mobility
SVM	Support Vector Machine
TAT	Traffic Analysis Tools
TAZ	Traffic Analysis Zone
TIA	Traffic Impact Analysis
TNC	Transportation Network Company
TOSAM	Traffic Operations and Safety Analysis Manual
TRANSIMS	Transportation Analysis and Simulation System
TRANSYT-7F	Traffic Network Study Tool Version 7F
TRL	Technology Readiness Level
U.S. DOT	United States Department of Transportation
USGS	United States Geological Survey
V2X	Vehicle-to-Everything
v/c	Volume to Capacity
VDOT	Virginia Department of Transportation
veh	Vehicle
veh/ln/mi	Vehicles Per Lane Per Mile
VHT	Vehicle Hours Traveled
VMT	Vehicle Miles Traveled
VRU	Vulnerable Road User

3 Review of AMS for ITS Tools Used in Practice

This chapter presents an overview of AMS for ITS tools typically used in practice. The identified tools are organized into principal 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 practice) 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 findings from the stakeholder interviews and continued literature review provided in the complementary State of Research 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 practice report as well as those from the concurrent State of Research 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 practice 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**: Outputs and/or metrics used to assess the tool's objectives.
- **Known Entities that Use the Tool and Select Use Cases**: Examples for how the tool is used in practice.
- **Summary**: Summary of key findings from the review of the tool including advantages and gaps/challenges in regard to practitioner use.

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

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 typically used in practice.

Furthermore, there are tools that are included in both this State of Practice report and the 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].

- Identified tools: No AMS tools that are part of typical practice and include at least one ITS component were identified with Sketch Planning as their principal category during interviews with stakeholders as well as the literature review. There are several tools from [13] that fall within this category, but these are either not supported anymore/are outdated or do not readily include ITS components.

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:
  - CUBE
  - TransCAD*
  - EMME
  - Visum*

3.2.1 CUBE

3.2.1.1 Tool Description

CUBE (CUBE Suite) is a travel demand modeling software tool used to analyze the effects of new projects and policies on a city's transportation network, land-use, and its population [14]. This tool's functionality includes urban, regional, and long-distance travel forecasting, freight forecasting, air quality analysis, and others. In order to use CUBE, users combine CUBE base, the system interface, with one or more CUBE extensions (e.g., CUBE Voyager for travel demand modeling) depending on the planning tasks [15]. The application manager of CUBE Voyager allows users to apply various modeling methodologies, including the trip-based (traditional four-step process), tour and activity-based modeling, as well as discrete choice methods [16], [17]. CUBE offers graphical user interfaces for generating the model chain that can be composed of existing models as well as the defined road network. CUBE is developed and marketed by Bentley Systems, Inc., and requires a paid license to access it.

3.2.1.2 Tool Category(ies)

Travel Demand Models, Mesoscopic Simulation (CUBE Avenue).

3.2.1.3 Primary Purposes/Objectives

CUBE is a transportation and land-use planning tool that enables transportation professionals to analyze the effects of new projects and policies on a city's transportation network, land-use, and its population. It provides users an opportunity to visualize and test a variety of scenarios to compare potential benefits and become aware of unexpected consequences. The information provided from these scenarios is expected to save time, money, review cycles, and debates as changes are proposed before delving further into the design process. CUBE has several extensions that perform different tasks within the transportation planning process (e.g., CUBE Land, CUBE Cargo, etc.) [18].

3.2.1.4 Scope (including applicable ITS component(s))

CUBE is a travel demand modeling tool and is typically not used to estimate changes at the tactical and operational levels of traffic management. In terms of ITS applications, CUBE does not directly model them. However, CUBE can be integrated with Dynameq, a mesoscopic tool to model and assess the impacts of 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

Data required for travel demand modeling using CUBE include the following:

- Geometric Data: Geographic Information System (GIS)-based network data including traffic analysis zones, jurisdiction boundaries, transportation network links and nodes, etc.
- Current Socioeconomic Data: number of households, population in households, vehicles, and employment in a traffic analysis zone (TAZ).
- Forecasts of future population, households, and employment throughout a TAZ.
- Transit Data.
- 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 CUBE include Average Traffic Volume, Vehicle Miles Traveled (VMT), Average Travel Times, Average Speeds, Transit Ridership, Total Trips, etc.

3.2.1.7 Known Entities that Use the Tool and Select Use Cases

Table 3. Examples of Known Entities that Use CUBE and Select Use Cases

Entity Type	Entity	Use Case	Link
State	Virginia DOT	VDOT uses CUBE to develop statewide and regional demand models.	VDOT Transportation Modeling and Accessibility Program [19]
State	California DOT	A statewide model for California that can forecast short- and long- distance travel by California residents.	California Statewide Travel Demand Model [20]
Region	Metropolitan Washington Council of Governments	A regional travel demand model for the Metropolitan Washington, DC Area.	Metropolitan Washington Council of Governments Travel Demand Forecasting Model [21]

3.2.1.8 Summary

Key findings from the review of CUBE include [14]:

- Its ability to visualize, test, and compare multiple scenarios in one application.
- Its use of flow charts to group processes to ensure completion of tasks.
- Its inclusion of one interface for land use and transportation system to support seamless communication and data sharing.
- Its ability to handle time of day and peak spreading models.
- Its ability to be integrated with Dynameq to create a multiresolution model.
- Additional skills and training may be required to make full use of the tool’s functionalities.
- Access to this tool requires a paid license.

3.2.2 TransCAD*

This tool is also discussed the State of Research report.

3.2.2.1 Tool Description

TransCAD is a transportation planning software that combines GIS and transportation modeling capabilities in a single integrated platform, providing a plethora of capabilities for transportation professionals. 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 routing, travel demand forecasting, public transit, logistics, site location, and territory management [22]. Developed by the Caliper Corporation, TransCAD uses the traditional four-step process, activity-based, demand model, and provides numerous discrete choice and assignment options. 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 [16]. TransCAD is a commercial tool and requires a paid license to obtain access.

3.2.2.2 Tool Category(ies)

Travel Demand Models, Sketch Planning.

3.2.2.3 Primary Purposes/Objectives

TransCAD is a transportation planning tool that supports methods for forecasting 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 [23].

3.2.2.4 Scope (including applicable ITS component(s))

TransCAD can model cities, regions, and country-wide travel demand. TransCAD does not directly model ITS applications. However, TransCAD can be integrated with TransModeler, a microscopic simulation tool, to assess the macro-level travel demand impacts of ITS applications such as ramp metering, transit signal priority, variable speed limits, hard shoulder running, and HOT lanes.

3.2.2.5 Data Inputs/Requirements

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

- Geometric Data: GIS-based network data including traffic analysis zones, jurisdiction boundaries, 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.

3.2.2.6 Performance Measures/Outputs

Some of the performance measures/outputs generated by TransCAD include Average Traffic Volume, VMT by traveler type, Average Travel Times, Average Speeds, Transit Ridership, Total Trips, Total Miles, etc.

3.2.2.7 Known Entities that Use the Tool and Select Use Cases

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

Entity Type	Entity	Use Case	Link
State Agency	Vermont DOT	A statewide transportation demand model for the state of Vermont.	Vermont Travel Model [24]
State Agency	Indiana DOT	Modeled and assessed the impacts of time-of-day tolling on Indiana roadways using TransCAD.	Evaluating Impacts of Time-of-Day Tolling on Indiana Roadways [25]
State Agency	Minnesota DOT	A TransCAD model to help quantify the expected impact of new capital projects on roadway snow and ice control operations.	Quantifying the Impact of New Capital Projects on RSIC Operations [26]

3.2.2.8 Summary

Key findings from the review of TransCAD include:

- The tool's use of a single platform that is able to perform multiple functions, including model application, model estimation, database support, GIS-based analysis, and often graphical and analytical postprocessing.
- 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 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.
- Additional skills and training may be required to make full use of the tool's functionalities.
- Access to this tool requires a paid license.

3.2.3 EMME

3.2.3.1 Tool Description

EMME is a multimodal transportation planning software. It serves as a transportation forecasting system for planning the movement of people at urban, regional, and national scales. Its primary applications include travel demand forecasting, traffic planning, transit planning, land-use modeling, economic and environmental analyses, as well as pedestrian, bicycle, and active transport planning. EMME has options to employ most aggregate or disaggregate travel demand model structures, including agent-based, trip-based, tour-based, and hybrid models. EMME enables users to identify major passenger trips between zones, facilitating the optimization of public transport routes and amenities. Additionally, it accounts for the impacts of crowding and capacity limitations on both public transportation routes/vehicles, and park-and-ride facilities. [27] – [29]

3.2.3.2 Tool Category(ies)

Travel Demand Models.

3.2.3.3 Primary Purposes/Objectives

EMME is used for travel demand forecasting, traffic planning, transit planning, economic analysis, environmental analysis, and pedestrian/bicycle/active transport planning. It can be used to evaluate changes to transit routes, frequency, quality of service, transit service competition or fare integration, crowding on transit vehicles and at stations, and walkability/accessibility. Further, EMME allows for the evaluation of road network expansion and management schemes, toll schemes and toll revenue forecasts, accessibility studies, and freight movements [27].

3.2.3.4 Scope (including applicable ITS components(s))

EMME is used for and sub-regional, regional, and national transportation modeling and analyses. It can be used to evaluate changes to transit routes, frequency, quality of service, transit service competition or fare integration, crowding on transit vehicles and at stations, and walkability/accessibility. This tool is also capable of modeling components of ITS such as emerging mobility, including CAVs [29].

3.2.3.5 Data Inputs/Requirements

Data required to conduct travel demand modeling and analysis using EMME include the following [30]:

- Network Data: Road and railway network data (obtained as GIS-based files) consisting of links and nodes representing roadway segments and intersections.

- Transit Data: This is usually derived from General Transit Feed Specification (GTFS) files which provide data on transit route attributes (e.g., transit route and lines, schedules, location and number of bus stops, bus types, headways, speed, etc.).
- Traffic Flow/Travel Demand Data: Origin-Destination Matrix, trip generation zones, capacity zones, household vehicle ownership data, transit fare and auto operating cost data, parking cost distribution data, population distribution data (including household socio-economic data), volume, delay, etc.

3.2.3.6 Performance Measures/Outputs

Some of the performance measures/outputs generated by EMME include Traffic Volumes, VMT, Average Travel Times, Average Speeds, Transit Ridership, Total Trips, Trip Lists, Trip Tables by Mode, Emissions Rates, Route/Line Profiles (to identify congestion on transit lines and sections where alighting and boarding are prominent), etc. [28], [29], [30]

3.2.3.7 Known Entities that Use the Tool and Select Use Cases

Table 5. Examples of Known Entities that Use EMME and Select Use Cases

Entity Type	Entity	Use Case	Link
City Agency	San Diego Association of Governments (SANDAG)	Utilized EMME for analyzing policies and transit investments related to border access highways at a sub-regional level, considering the uncertainty stemming from shifting demographics, land use, border access, and emerging vehicle technologies.	Travel Model Improvement Program Exploratory Modeling and Analysis Tool (TMIP-EMAT) Beta Test Results [31]
City Agency	Chicago Metropolitan Agency for Planning (CMAP)	Employed EMME for travel demand modeling and analysis for various Northeastern Illinois Transportation Improvement Program projects.	On to 2050 Travel Demand Model Documentation [30]

3.2.3.8 Summary

Key findings from the review of EMME include:

- Its support of open data standards and Python code scripting.

- EMME allows for inclusion/development of models that can be tailored to support local/user-specific applications [32].
- Its support of traditional four-step demand model and agent-based demand modeling [33].
- Its support of code-free assembling and running of travel demand models through the use of an automation system called Flow [33].
- Its inclusion of transit assignment features that support the modeling of mixed-mode assignment sequences such as driving, Transportation Network Companies (TNCs) pick-up, scooter use, etc. [33].
- It can be integrated with other modeling tools such as Aimsun Next, MOVES, and GIS-based tools [30], [34], [35].
- Additional skills and training may be needed to effectively use the tool.
- Access to EMME requires a paid license.

3.2.4 Visum*

This tool is also discussed the State of Research report.

3.2.4.1 Tool Description

Visum is a simulation tool used for transportation planning, travel demand modelling, and network data management. Primarily, most agencies use Visum as a travel demand modeling tool. 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, trip-based (four-step process), and activity-based modeling approaches [21]. This tool's demand modeling 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 with suites of analysis tools for transportation planning. Visum is developed by the PTV Group and requires paid license to obtain access [36].

3.2.4.2 Tool Category(ies)

Travel Demand Models, Macroscopic Simulation, Mesoscopic Simulation.

3.2.4.3 Primary Purposes/Objectives

Visum is primarily used to assist transportation agencies plan for future investments in transportation infrastructure and sustainable mobility. This is achieved by performing multimodal simulation of the transportation system and forecasting demand for various scenarios [37]. Results from Visum models are intended to help an agency to develop a transportation improvement master plan based on which operational and infrastructure enhancements yield the best performance.

3.2.4.4 Scope (including applicable ITS component(s))

Visum is a traffic demand modelling tool that models transportation networks at the city and regional levels. Since ITS applications are often implemented at the microscopic and mesoscopic models, Visum does 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.

3.2.4.5 Data Inputs/Requirements

Data required to conduct travel demand modeling and 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.

3.2.4.6 Performance Measures/Outputs

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

3.2.4.7 Known Entities that Use the Tool and Select Use Cases

Table 6. Examples of Known Entities that Use Visum and Select Use Cases

Entity Type	Entity	Use Case	Link
State Agency	Florida DOT	A multiresolution model using Visum and Vissim to study the impacts of deploying Complete Streets in Florida.	Impacts of Complete Streets in Urban Corridors [38]
City Agency	Salt Lake City, UT	A Visum model to evaluate and compare three construction scenarios in Salt Lake City, UT.	Utah DOT I-15 Reconstruction [39]
City Agency	Duvall, WA	A Visum travel demand model to evaluate transportation needs in coordination with long-term planning in the City of Duvall, WA.	Visum Travel Demand Model - Duvall [40]

3.2.4.8 Summary

Key findings from the review of Visum include [37]:

- Its inclusion of a graphical user interface (GUI) that enables 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.

Fidelity and/or Resolution: For analytical and deterministic tools, modeling is done at the macroscopic level and has a lower fidelity compared to microscopic level tools.

- Identified Tools:
  - Highway Capacity Software HCS
  - SIDRA Intersection

3.3.1 Highway Capacity Software

3.3.1.1 Tool Description

Highway Capacity Software (HCS) implements methods and procedures documented in the HCM. The HCS includes several modules with methodologies from the HCM, including those for network, freeway, highway, arterial, etc. service volumes analyses, to evaluate different facilities and roadway geometric configurations within a transportation network [41]. HCS is utilized by practitioners to analyze freeway segments, freeway facilities, and urban streets and arterials with signalized intersections. The tool is also used to model intersections with stop control and signalization, roundabouts, and freeway facilities such as ramps and interchanges [42].

3.3.1.2 Tool Category(ies)

Analytical/Deterministic [42].

3.3.1.3 Primary Purpose(s)/Objective(s)

HCS is used for both planning and operational studies for urban streets, intersections, freeways, and arterials. It has the capability of modeling innovative/alternative intersection types such as the Median U-Turn (MUT), Restricted Crossing U-Turn (RCUT), and Displaced Left Turn (DLT). HCS is also used to analyze ramp terminals and interchanges including Diamond Interchanges, Single-Point Urban Interchange (SPUI), and Diverging Diamond Interchange (DDI) [42].

3.3.1.4 Scope (including applicable ITS component(s))

HCS is used for link and network wide (comprising of urban streets, arterials, and freeways) analysis, including work zones. This tool is also capable of modeling parts/components of ITS applications. Examples include HOV/HOT lanes, traffic signal timing optimization (such as when HCS is integrated with Traffic Network Study Tool Version 7F [TRANSYT-7F] or other traffic optimization tools), and active traffic management for arterials and freeway Segments [42].

3.3.1.5 Data Inputs/Requirements

Data required to conduct traffic analysis using HCS include the following:

- Geometric Data and Analysis Settings: Acceleration and deceleration lengths, adjacent ramp configuration, free flow speed, demand, passing lane analysis, number of transit stops, ramp free-flow speed, segment length, segment type, terrain, highway class, etc.
- Traffic Flow/Travel Demand Data: Traffic volumes, heavy vehicle percentages, percent trucks, Peak Hour Factor (PHF), etc.
- Signal Timing Data: Phasing, red clearance time, cycle length, yellow interval, offset, walk interval, pedestrian clearance interval, etc. [41].

3.3.1.6 Performance Measures/Outputs

Traffic operations performance measures/outputs generated from HCS include 95th Percentile Queue (ft), Control Delay (sec), Percent of Free-flow Speed (%), Percent Time Spent Following (%), Density (veh/ln/mi)), Experienced Travel Time (sec/veh), Travel Time (sec and/or min), Space Mean Speed (mph), Level of Service (LOS), Volume to Capacity (v/c) Ratio, etc.

3.3.1.7 *Known Entities that Use the Tool and Select Use Cases*

Table 7. Examples of Known Entities that Use HCS and Select Use Cases

Entity Type	Entity	Use Case	Link
State Agency	Virginia DOT	Analysis of basic and weaving freeway segments, multilane highways, and two-lane highways.	Traffic Operation and Safety Analysis Manual [41]
State Agency	Florida DOT	• Capacity analysis and traffic signal coordination for urban arterials. • Operational analysis of rural two-lane highways and multilane highways. • Express lane analysis on limited access facilities. • Capacity analysis of weaving segments and ramp merge/diverge areas for interchanges.	Traffic Analysis Handbook [43]
State Agency	Washington DOT	Operational and design analysis of freeway segments, weaving areas, ramp and ramp terminals, multilane highways, two-lane highways, intersections, and transit.	Traffic Analysis Procedures Manual [44]
State Agency	Texas DOT	Analysis of freeway segments, weaving areas, ramp and ramp terminals, multi-lane highways, two-lane highways, and arterials.	Traffic Safety and Analysis Procedures Manual [45]

3.3.1.8 *Summary*

Key findings from the review of HCS include:

- The tool requires fewer inputs and less time for calibration, analysis, and modeling compared to other tools.
- Its ability to perform multi-time period analysis, which enables modeling of congestion and queues on arterials and freeways that stretch beyond peak periods [42].

- The user interface in HCS is not as visually intuitive as those included in other tools.
- This tool is unable to model some lane configurations [46].
- Access to HCS requires a paid license and the tool may require some initial training to effectively use it.

3.3.2 Sidra Intersection

3.3.2.1 Tool Description

Sidra Intersection is a software tool designed for the macro-level analysis of individual intersections as well as interconnected networks of intersections. It uses a lane-based micro-analytical model coupled with lane-based vehicle path (drive-cycle) models and an iterative approximation method. This enables the identification of traffic phenomena such as congestion, mid-block lane changes, and uneven lane usage at closely spaced intersections. Sidra also provides the option of implementing the HCM methodologies. Additionally, the tool can evaluate various types of intersections, including signal-controlled, roundabouts, and stop sign-controlled intersections, all in a single network. [47]

3.3.2.2 Tool Category(ies)

Analytical/Deterministic.

3.3.2.3 Primary Purpose(s)/Objective(s)

Although Sidra Intersection may be used to analyze signalized and unsignalized intersections as well as roundabouts, its primary application in the United States has been specifically for roundabout analysis [48].

3.3.2.4 Scope (including applicable ITS component(s))

Sidra Intersection may be used to analyze single intersections through networks of intersections. This tool has also been used to model ITS applications such as metered roundabouts [47], [49].

3.3.2.5 Data Inputs/Requirements (for roundabout analysis)

Data required to conduct traffic analysis using Sidra Intersection include the following:

- Geometric Data and Analysis Settings: Lane configuration, circulating width, entry angle and radius, island diameter, circulating lanes, capacity model (Sidra standard or HCM), environmental factor, peak flow factor, extra bunching, etc. [41], [43].
- Traffic Flow/Travel Demand Data: Traffic volumes, heavy vehicle percentages, etc.

3.3.2.6 Performance Measures/Outputs

Traffic operations performance measures/outputs generated from Sidra Intersection include 95th Percentile Vehicle Queues, Degree of Saturation, LOS, Control Delay, Number of Vehicle Stops, v/c Ratio, and Space Mean Speed [41], [43].

3.3.2.7 Known Entities that Use the Tool and Select Use Cases

Table 8. Examples of Known Entities that Use Sidra and Select Use Cases

Entity Type	Entity	Use Case	Link
State Agency	Virginia DOT	Roundabout Analysis.	Traffic Operations and Safety Analysis Manual (TOSAM) - Version 2.0 [41]
State Agency	Florida DOT	Roundabout Analysis.	FDOT Traffic Analysis Handbook [43]
State Agency	Washington DOT	Roundabout Analysis.	Traffic Analysis Procedures Manual [44]
State Agency	Texas DOT	Roundabout Analysis.	Traffic Safety and Analysis Procedures Manual [45]
State Agency	Colorado DOT	Roundabout Analysis.	Traffic Analysis and Forecasting Guidelines [46]

3.3.2.8 Summary

Key findings from the review of Sidra Intersection include [47]:

- Its ability to account for the effects of vehicle arrivals based on adjacent traffic control devices.
- Its use of a lane-based model that can identify backward spread of congestion, midblock lane changes and unequal approach lane use at closely spaced intersections, which is different from many tools that model traffic at intersections based on lane groups.
- In the United States, the use of Sidra is almost exclusively limited to roundabout analysis [48].
- Access to the tool requires a paid license, and the tool may require some initial training to effectively use it.

3.4 Traffic Optimization

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

Fidelity and/or Resolution: For traffic signal optimization tools, modeling is done at the macroscopic level and has a lower fidelity compared to microscopic and mesoscopic level tools.

- Identified tools:
  - Synchro
  - Vistro

3.4.1 Synchro

3.4.1.1 Tool Description

Synchro is a deterministic tool primarily used for analyzing traffic flow, traffic signal progression, and performing traffic signal timing optimization on arterials. By default, Synchro uses the Intersection Capacity Utilization (ICU) methodology. Additionally, Synchro implements the methods of the HCM, including the 2000, 2010, and 2016 editions [41], [50], [51]. Further, Synchro uses an exhaustive search technique to optimize signal timings. For example, to optimize timings for an arterial, the tool requires the user to apply several manual steps including cycle length optimization followed by offset and phase sequence optimization. It optimizes cycle length by analyzing all cycles in the defined range. For offsets optimization, Synchro uses a multi-stage process [52].

3.4.1.2 Tool Category(ies)

Traffic Optimization, Analytical/Deterministic.

3.4.1.3 Primary Purposes/Objectives

Synchro is used for policy, planning, and operational purposes. For example, at the project planning level Synchro is used by state agencies to determine the suitability of project alternatives and determine viable improvements based on anticipated traffic growth. Examples of planning level analysis for which Synchro used include corridor studies, intersection evaluations, and traffic impact analysis. At the operational level, Synchro is used to determine roadway and signal impacts to project areas. Examples of operational analysis for which Synchro is used include signal retiming, corridor operational assessments, and capacity analysis of individual intersections (signalized, unsignalized, or roundabout) [41].

3.4.1.4 Scope (including applicable ITS component(s))

Synchro is used for link and network wide (comprising of arterials) analysis. This tool is also capable of modeling ITS applications. Examples include adaptive traffic signal control, variable speed limit, and reversible lanes, which is possible with the creation of multiple models to capture network dynamics but is not a built-in feature.

3.4.1.5 Data Inputs/Requirements

Data required to conduct traffic analysis using Synchro include the following:

- Geometric Data and Analysis Settings: Link length, link speed, lane width, storage length, taper lengths, lane configuration, adjacent parking lanes, PHF [41].
- Traffic Flow/Travel Demand Data: Traffic volumes, heavy vehicle percentages.
- Signal Timing Data: All-red time, cycle length, maximum green mode, maximum/minimum recall, minimum green time, total split, offset reference, yellow time, flash don't walk time, walk time [41].

3.4.1.6 Performance Measures/Outputs

Traffic operations performance measures/outputs generated from Synchro include 95th Percentile and Maximum Queue Lengths (ft), Control Delay (sec), LOS, Travel Time (min), Space Mean Speed (mph), v/c Ratio, etc.

3.4.1.7 Known Entities that Use the Tool and Select Use Cases

Table 9. Examples of Known Entities that Use Synchro and Select Use Cases

Entity Type	Entity	Use Case	Link
State Agency	Virginia DOT	Intersection, arterial, and corridor analysis.	Traffic Operations and Safety Analysis Manual (TOSAM) - Version 2.0 [41]
State Agency	Florida DOT	• Capacity analysis and traffic signal optimization on urban arterials. • Network and system performance evaluation.	FDOT Traffic Analysis Handbook [43]
State Agency	Wisconsin DOT	Capacity analysis and traffic signal optimization on urban arterials.	• Traffic Operation and Safety Analysis Manual: TEOpS 16-20 [53] • Traffic Analysis Tool Selection: Flow Chart [54]

3.4.1.8 Summary

Key findings from the review of Synchro include [50]:

- Its ability to model corridors of signalized and unsignalized intersections.
- Its ability to optimize splits, cycle lengths, phase sequences and offsets.
- Its inclusion of an interactive GUI.
- Synchro is not well-suited for the analysis of freeways, interchange systems, and ramps [55] and may not accurately model oversaturated traffic conditions.
- The latest HCM edition was released in 2022, however, it is unclear to what extent the latest version of Synchro incorporates this edition as well as its adoption in practice.
- Access to this tool requires a paid license.

3.4.2 Vistro

3.4.2.1 Tool Description

Vistro is a traffic signal optimization engineering software for traffic signal analyses and traffic impact studies. It has a traffic signal workflow that allows it to set up and create fixed time, semi-actuated, and fully actuated signals. Vistro can perform traffic optimization at individual intersections, for districts, or across the entire network. Vistro offers different analysis methodologies to meet the needed requirements, including those in the HCM (for local optimization), Intersection Capacity Utilization (ICU), platoon dispersion model (for network optimization), etc. [56]. Vistro supports file integration from Synchro and import/export capabilities with, Visum and Visum. Furthermore, Vistro's traffic signal control outputs can integrate with Vissim and Visum [56], [57].

3.4.2.2 Tool Category(ies)

Traffic Optimization, Analytical/Deterministic.

3.4.2.3 Primary Purpose(s)/Objective(s)

Vistro is used for traffic signal optimization and analysis for standard and advanced signalization needs in coordinated and uncoordinated environments, as well as for traffic impact analysis (TIA).

3.4.2.4 Scope (including applicable ITS component(s))

Vistro is mainly used for traffic signal analysis and optimization and is capable of modelling alternative intersection designs such as Restricted Crossing U-Turn, Single Point Urban Interchange, Green-T, Continuous Flow Intersection, and Diverging Diamond Interchange designs. It can also be used to model advanced traffic signal optimization at individual intersection, districts, or across the entire network [57]. Vistro integrates pedestrian, bicycle, and vehicular traffic for network optimization [57]. With updates to the HCM, Vistro can perform analysis that includes CAV market penetration rates, adjusted saturation flow rates, and other traffic adjustment factors for signalized intersections as well as roundabouts. [58]

3.4.2.5 Data Inputs/Requirements (for roundabout analysis)

Data required to conduct traffic analysis and optimization using Vistro include the following [56]:

- Geometric Data and Analysis Data: Arrival distribution, auxiliary lane length, car-following model, entry traffic volumes, link length link speed, desired speed distributions, and 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 Data: 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.

3.4.2.6 Performance Measures/Outputs

Performance measures/outputs generated from Vistro include Intersection LOS, Turning Movement LOS, Intersection and Turning Movement Delays, v/c Ratios, Intersection Throughput, Turning Movement Throughput, Trave Times, etc. [56]

3.4.2.7 Known Entities that Use the Tool and Select Use Cases

Table 10. Examples of Known Entities that Use Vistro and Select Use Cases

Entity Type	Entity	Use Case	Link
County Agency	Santa Clara Valley Transportation Authority (VTA)	Utilize Vistro to analyze a large network of intersections for congestion management monitoring and congestion relief corridor planning studies in Santa Clara Valley, CA.	Intersection analysis: PTV Vistro eases Silicon Valley traffic [59]

Entity Type	Entity	Use Case	Link
State Agency	North Carolina DOT	Utilized Vistro to optimize signal timings for real-world intersection development planning scenario simulation in North Carolina.	Operational Applications of Signalized Offset T-Intersections [60]

3.4.2.8 Summary

Key findings from the review of Vistro include:

- Its network and signal optimization capabilities.
- The tool is capable of modeling pedestrian and bicycle phases.
- Its incorporation of adaptable traffic signal workflows.
- It implements HCM methodologies for signalized intersections, stop-controlled intersections, and roundabouts [46].
- It is compatible with Vissim and Visum.
- Its inability to model ramp terminals [46].
- Access to Vistro requires a paid license.
- Additional skills/training may be needed to effectively use the tool.

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].

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

- Identified tools:
    - FREEVAL
    - Other tools with other principal tool categories have a macroscopic simulation secondary tool category. See the travel demand models, analytical/deterministic, mesoscopic simulation, and microscopic simulation tool category sections for more information.

3.5.1 FREEVAL

3.5.1.1 Tool Description

FREeway EVALuation (FREEVAL) is a macroscopic analysis tool designed to perform operational analysis computations for undersaturated and oversaturated directional freeway facilities. FREEVAL implements methodologies presented in several chapters of the HCM, which incorporate freeway segment analysis procedures for basic freeway segments, weaving segments, and merge and diverge segments. FREEVAL can be used to analyze operations of individual freeway segments or an entire directional facility [61].

3.5.1.2 Tool Category(ies)

Macroscopic Simulation, Analytical/Deterministic.

3.5.1.3 Primary Purpose(s)/Objective(s)

FREEVAL is used for freeway planning-level capacity analyses for undersaturated and oversaturated conditions. It also provides work zone impact assessments for planning-level and operational-level analyses. Further, it is used for the evaluation of managed lanes such as high occupancy vehicle (HOV), HOT, and expressways [61].

3.5.1.4 Scope (including applicable ITS component(s))

FREEVAL is used for freeway analysis. This tool is also capable of modeling parts/components of ITS applications for traffic incident management, weather traffic management, and work zone traffic maintenance. Examples include end-of queue advanced warning systems, variable message signs, portable message signs, automatic collision warning systems, etc.

3.5.1.5 Data Inputs/Requirements

Data required to conduct macroscopic simulation and traffic analysis using FREEVAL include the following:

- Geometric Data and Analysis Settings: Number of mainline lanes, number of ramp lanes, acceleration/deceleration lanes, jam density, area type, general purpose segment type, general purpose vehicle occupancy, capacity drop due to breakdown, study period start and end times, number of HCM segments, mainline and ramp free-flow speed, terrain, etc. [41].
- Traffic Flow/Travel Demand Data: Traffic volumes, percent trucks and buses/percent recreational vehicles.

3.5.1.6 Performance Measures/Outputs

Traffic operation performance measures/outputs generated from FREEVAL include 95th, 80th, and 50th Percentile Travel Time Indices, Density (pc/mi/ln), Demand to Capacity Ratio, Space

Mean Speed (mph), Vehicle Miles Traveled (veh-miles/interval), Passenger Miles Traveled (p-miles/interval), Vehicle Hours (travel/interval [hrs]), Vehicle Hours Delay (delay/interval [hrs]), and User Cost ($) [41], [61].

3.5.1.7 Known Entities that Use the Tool and Select Use Cases

Table 11. Examples of Known Entities that Use FREEVAL and Select Use Cases

Entity Type	Entity	Use Case	Link
State Agency	Virginia DOT	Individual Freeway Segment Analysis.	Traffic Operation and Safety Analysis Manual [41]
State Agency	Pennsylvania DOT	Freeway Work Zone Analysis.	PennDOT Predictive Analysis for Work Zones [62]
State Agency	North Carolina DOT	Freeway Work Zone and Reliability Analysis.	FREEVAL NC Users Guide [63]
State Agency	Texas DOT	Freeway, Multi-lane Highway, Two-lane Highway, and Managed Lanes Analysis as well as Travel Time and Reliability Analysis.	Texas Traffic Safety and Analysis Procedures Manual [45]

3.5.1.8 Summary

Key findings from the review of FREEVAL include:

- Its ability to model both undersaturated and oversaturated conditions [61].
- This is a free open-source tool maintained by the TRB Committee on Highway and Quality of Service [61].
- The tool does not incorporate a graphical interface that can visualize segment coding, which has been shown to make analysts prone to making mistakes when entering network geometries, particularly for large networks [64].
- Users have identified the existence of inconsistencies between demand variability over time and facility travel time that may arise if facility length exceeds 9 -12 miles [61].
- Additional skills and training may be required to make full use of the tool's functionalities.
- Since it is an open-source tool, there is limited technical support available to users.

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 [65]. 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 [66]. Outputs from mesoscopic models include time-varying traffic flow dynamics and traveler path choice behavior. There are many commercial and research-based (or open-source) mesoscopic simulation tools at the disposal of transportation practitioners. However, a few are presented in this report to highlight the different flavors in terms of methodology, complexity, and level of usage by transportation practitioners.

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:
  - DYNASMART
  - DynusT
  - Dynameq

3.6.1 DYNASMART

3.6.1.1 Tool Description

DYnamic Network Assignment-Simulation Model for Advanced Road Telematics (DYNASMART) is a discrete time mesoscopic simulation model for advanced traffic management system and advanced traveler information system applications. It is designed to model traffic patterns and evaluate overall network performance under real-time information systems [67]. This tool was developed and tested under FHWA's Dynamic Traffic Assignment (DTA) project [68]. A key feature of DYNASMART is the modeling of dynamic routing behavior of vehicles/travelers in a network as opposed to static assignment [69]. DYNASMART simulates individual vehicles along paths selected out of k-shortest paths, and vehicles make route decision based on their characteristics and information acquisition capability. It also incorporates real-time control systems that are classified based on their algorithm structures. The algorithm structures include user optimal vs. system optimal, instantaneous vs. predictive, open-loop vs. closed-loop system. Furthermore, four routing approaches are used based on the control system selected. The routing approaches include simple feedback, simple predictive, predictive DTA, and DTA Feedback [70]. Currently, two versions of DYNASMART are available through the DTA project: DYNASMART-X for real-time analysis and DYNASMART-P for planning. DYNASMART-P provides the capability to model the evolution of traffic flows in a traffic network, which result from the decisions of individual travelers seeking the most optimal route over a given planning horizon. DYNASMART-P is available from the Center for Microcomputers in Transportation (McTrans) [71]. Inheriting the core simulation components from the offline planning tool (DYNASMART-P), the primary distinction of the online operational tool (DYNASMART-X) is its capability of interacting with multiple sources of real-time information and providing reliable estimates of network traffic conditions and predictions of network flow patterns [72]. Both DYNASMART-P and DYNASMART-X are open-source tools and do not require paid license to access.

3.6.1.2 Tool Category(ies)

Mesoscopic Simulation.

3.6.1.3 Primary Purposes/Objectives

DYNASMART is an intelligent transportation network operational planning tool. The offline model (DYNASMART-P) models the evolution of traffic flows in a traffic network from the travel decisions of individual drivers and is designed for use in urban areas of various sizes. The online model (DYNASMART-X) provides real-time prediction of network traffic conditions and flow patterns based on real-time data from multiple sources [73].

3.6.1.4 Scope (including applicable ITS component(s))

DYNASMART models links and networks at the mesoscopic level and is capable of modeling urban areas of various sizes as well as work zones and evacuation zones. This tool is capable of modeling and simulating ITS applications such as ramp metering, variable message signs, in-vehicle traveler information, incident management, HOT lanes, etc. [74].

3.6.1.5 Data Inputs/Requirements

Data required to model and simulate using DYNASMART 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, signs and markings, etc.
- Traffic Control Data: Signal timing data (control type, number of phases, cycle length, maximum green, minimum green, offset, amber time), lane markings, turning signs, etc.
- Traffic Flow/Travel Demand Data: O-D matrices, travel times, travel speeds, etc.
- Vehicle Classes: Passenger cars, buses, trucks, etc.
- User Classes: Unresponsive users, VMS responsive users, Users with in-vehicle information, etc.

3.6.1.6 Performance Measures/Outputs

Traffic operations performance measures/outputs generated from DYNASAMRT include Total Travel Time, Average Travel Time, Vehicle Throughput, Travel Time Index, Buffer Index, Planning Time Index, Misery Index, Total Stopped Time Savings, Percentage of Vehicles Stopped, Stopped Time, etc. [74].

3.6.1.7 Known Entities that Use the Tool and Select Use Cases

Table 12. Examples of Known Entities that Use DYNASMART and Select Use Cases

Entity Type	Entity	Use Case	Link
State Agency	Utah DOT	Integrated and operationalized weather-sensitive DYNASMART-X models calibrated for the Salt Lake City region to support weather-responsive traffic signal timing implementation and evaluation in the Riverdale corridor in Ogden, UT.	Weather Responsive Traffic Estimation [72]
State Agency	Maryland State Highway Administration	Application of DYNASMART-X to Maryland's Coordinated Highways Action Response Team (CHART) network along the I-95 corridor between Washington, DC and Baltimore, MD.	DYNASAMRT-X Evaluation for Real-Time TMC Application [75]

3.6.1.8 Summary

Key findings from the review of DYNASMART include:

- Its ability to model and simulate in both offline (i.e., planning mode) and online (i.e., operational) modes [76].
- Its ability to model individual drivers' response to information based on a set of paths rather than the single shortest path [67].
- Its ability to expand capabilities and functionality through multiple means (e.g., Application Programming Interface [API]) [73].
- Its ability to model scenarios with only a fraction of the vehicles equipped to receive travel information [67].

- The tool is open-source and does not require a paid license to access [73].
- Since it is an open-source tool, there is limited technical support available to users.
- DYNAMSMART requires significant efforts/resources to extend tool's capability through the API [73].
- This tool does not model bicycle/pedestrian paths, transit roadways and facilities, or parking management [77].
- Additional training and skills may be needed to effectively use the tool.

3.6.2 DynusT

3.6.2.1 Tool Description

Dynamic Urban Systems for Transportation (DynusT) is a simulation based DTA model that can support engineers and planners to address emerging transportation planning and operation challenges. This mesoscopic tool can estimate the evolution of system-wide traffic flow dynamics patterns that result from individual drivers seeking the most optimal routes to their destinations and respond to changing network demand, supply, or control conditions [78]. Traffic or user behavior simulation in DynusT is based on an anisotropic mesoscopic simulation model, which is a vehicle-based approach that explicitly considers traffic flow's anisotropic property during the vehicle state update at each time step in the simulation [79]. Additionally, DynusT has been noted for its computational efficiency [80]. DynusT is developed and licensed by Metropia Inc. [81].

3.6.2.2 Tool Category(ies)

Mesoscopic Simulation.

3.6.2.3 Primary Purposes/Objectives

DynusT is a mesoscopic simulation tool used to model and assess system-wide traffic flow dynamics based on traveler response to information and prevailing traffic/travel conditions. This tool helps transportation professionals respond to traffic operation challenges by allowing them to test various strategies and assessing their impacts efficiently in a simulation environment [78].

3.6.2.4 Scope (including applicable ITS component(s))

DynusT models links and networks at the mesoscopic level and can perform DTA on regional-level networks over a long simulation period. This makes DynusT well-suited for regional-level modeling such as regional transportation planning, corridor studies, integration with activity-based models, and mass evacuation modeling [80]. DynusT can model and simulate ITS technologies such as dynamic message signs, ramp meters, in-vehicle guidance systems, and strategies such as work zone management, incident management, and special event management [78].

3.6.2.5 Data Inputs/Requirements

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

- Geometric Data: GIS-based network that includes lane width, lane length, main lanes, left/right turn bays, etc.
- Traffic Control Data: Signal timing data, stop sign controls, U-turn flags, etc.
- Traffic Flow/Travel Demand Data: Trip tables for different user classes including Single Occupant Vehicle (SOV) O-D matrix, HOV O-D matrix, and truck O-D matrix, travel times, travel speeds, etc.
- Vehicle Classes: Single occupant vehicles, high occupant vehicles, and trucks.
- User Classes: Specification of which of the 10 user classes are desired, which enable flexibility in handling a wide range of scenarios, such as SOVs not paying a toll, SOVs paying a toll, HOVs not paying a toll, trucks not allowed to enter restricted areas, etc.

3.6.2.6 Performance Measures/Outputs

Traffic operations performance measures/outputs generated from DynusT include Travel Time, Travel Speed, VMT, Delay, etc. These performance measures can be estimated for each user class at the link/lane level, path-level, or network level [82].

3.6.2.7 Known Entities that Use the Tool and Select Use Cases

Table 13. Examples of Known Entities that Use DynusT and Select Use Cases

Entity Type	Entity	Use Case	Link
Federal Agency	FHWA	DynusT used to model the following ICM strategies: ramp metering, congestion pricing, and transit simulation and assignment, for various incident scenarios. The city of Minneapolis, MN was used as study location.	Traffic Analysis Toolbox – Volume XIV [83]
State Agency	Michigan DOT	DynusT used to model various work zone traffic management scenarios in Detroit, MI.	DynusT Applications Examples [84]

Entity Type	Entity	Use Case	Link
County	Maricopa Association of Governments	DynusT used to model of the regional road network in Maricopa County, GA to study operational strategies intended to mitigate impacts of work zones, crashes, road closures, etc.	Application of DynusT for Regional Traffic Operations [85]

3.6.2.8 Summary

Key findings from the review of DynusT include [78]:

- Its anisotropic mesoscopic simulation property that increases the simulation speed and allows for computational efficiency.
- Its ability to model a wide range of scenarios that include passenger vehicles, trucks, and HOV lane restrictions, and other user road classes.
- Its ability to specify time-varying O-D matrices in a wide range of time resolutions from minutes to hours.
- Its ability to be integrated with activity-based models (ABMs) [86].
- The tool requiring significant efforts/resources to extend the tool's capabilities through its API [73].
- Its inability to explicitly define individual lanes, therefore not allowing lane-level phenomena to be replicated. Also, it is not able to model ring barrier controllers [87] or pedestrian/bicycle paths [78].
- Access to DynusT requires a paid license and the tool may require additional skills and/or training to effectively use it.

3.6.3 Dynameq

3.6.3.1 Tool Description

Dynameq is a mesoscopic dynamic traffic assignment tool with microscopic simulation properties developed by INRO, a company based in Canada [87]. According to INRO, Dynameq's traffic simulation is often referred to as mesoscopic due to its ability to calibrate and simulate a larger network scale compared to other microscopic models. This tool utilizes an iterative approach to determine the optimal allocation of time-varying origin-destination demands to routes within a road network. The travel times on these routes, which are contingent on the distribution of traffic across them, are also time-varying and are calculated using an intricate traffic simulation model [88]. Dynameq models and simulates the movement of individual vehicles with car-following models, gap-acceptance models, and explicit signal timings [89]. Dynameq is a commercial tool that requires a paid license to access.

3.6.3.2 Tool Category(ies)

Mesoscopic Simulation.

3.6.3.3 Primary Purposes/Objectives

Dynameq provides the ability for transportation professionals to analyze existing transportation network issues and plan for improvements. This tool can simulate multimodal traffic conditions as well as model different mitigating strategies [89].

3.6.3.4 Scope (including applicable ITS component(s))

Dynameq provides scalability from a single congested corridor to an entire city, all without losing detail. This tool can model many ITS strategies and applications including ramp metering, transit signal priority, variable speed limits, hard shoulder running, and HOT lanes. Dynameq can also model transit-focused strategies such as bus rapid transit and light rail transit. [89]

3.6.3.5 Data Inputs/Requirements

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

- Geometric Data: Lane width, lane length, intersection locations, etc.
- Traffic Control Data: Signal timing data (cycle length, phase, and coordination offset, etc.), stop sign controls, etc.
- Traffic Flow/Travel Demand Data: O-D matrix for different vehicle types, travel times, travel speeds, etc.
- Vehicle Classes: Passenger vehicles, buses, trucks, light rail, etc.
- Vehicle Characteristics: Vehicle make, length, width.

3.6.3.6 Performance Measures/Outputs

Traffic operations performance measures/outputs generated from Dynameq include Travel Time, Travel Speed, VMT, Delay, Queues, etc. These performance measures/outputs can be estimated for each road user/vehicle class at the lane level, path-level, or network level [73].

3.6.3.7 Known Entities that Use the Tool and Select Use Cases

Table 14. Examples of Known Entities that Use Dynameq and Select Use Cases

Entity Type	Entity	Use Case	Link
County	San Francisco County	Dynameq-based DTA model for the entire city of San Francisco, CA to enable effective evaluation of projects within the region.	The DTA Anyway Project [90]
City	Edmonton, Canada	Dynameq citywide traffic simulation and DTA model to assess multiple operational planning studies in support of the Transportation Master Plan for city of Edmonton, Alberta, and its holistic view of transport as an interconnected, multimodal system.	Dynameq Case Study – Edmonton [91]
City	Kansas City	Dynameq-based corridor model to evaluate potential improvement strategies along I-70 in Kansas City, MO.	Dynameq Case Study – Kansas City [92]

3.6.3.8 Summary

Key findings from the review of Dynameq include [87]:

- Its ability to simulate vehicles at the lane level.
- Its ability to model multiple scenarios with a variety of modes that include passenger vehicles, trucks, and HOV lane restrictions.
- Its ability to model restricted movements such as lane restrictions for vehicle types and vehicle occupancy requirements.
- Its ability to model roundabouts and rotaries.
- Its capabilities can be extended using the tool’s Python-based API.
- Its inability to model pedestrian/bicycles paths [87] and requiring additional resources to extend the tool’s capability through its API [73].
- Access to Dynameq requires a paid license, and the tool may require additional training and skills to effectively use it.

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:
  - Vissim*
  - SimTraffic
  - Aimsun*
  - Paramics*
  - CORSIM*
  - TransModeler*
  - TRANSIMS
  - SUMO*

3.7.1 Vissim*

This tool is also discussed the State of Research report.

3.7.1.1 Tool Description

Vissim is a 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 [93]. 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. Vissim, in conjunction with another PTV product called Viswalk, is able to analyze and simulate pedestrians [94], [95]. 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 [95].

3.7.1.2 Tool Category(ies)

Microscopic Simulation.

3.7.1.3 Primary Purposes/Objectives

Vissim is used for policy, planning, and operational purposes. For example, at the project planning level Vissim is used by state agencies to develop and select preferred alternatives that can be shared with stakeholders for investment decisions and to determine viable improvements based on anticipated traffic growth. At the operational level, Vissim is used by state agencies, consultants, academia etc., for traffic impact analysis, interchange justification/modification studies, and work zone hours of operation analysis [41]. Other purposes of Vissim include evacuation planning, 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 [96].

3.7.1.4 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 [96].

3.7.1.5 Data Inputs/Requirements

Data required to perform simulation using Vissim include the following [41]:

- 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.

3.7.1.6 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), O-D Pair Results, Pedestrian Analysis Results (Maximum/Minimum Number of Pedestrians, Density, Speed, Travel Time, Delay, etc.), Emissions, Fuel Consumption [41].

3.7.1.7 Known Entities that Use the Tool and Select Use Cases

Table 15. Examples of Known Entities that Use Vissim and Select Use Cases

Entity Type	Entity	Use Case	Link
State Agency	Virginia DOT	Arterial and freeway operation studies, toll plaza and gated analyses, managed lane or ramp metering analyses.	Traffic Operations and Safety Analysis Manual (TOSAM) - Version 2.0 [41]
State Agency	District of Columbia DOT	Freeway operation studies, transit modeling.	DDOT Design and Engineering Manual [97]
State Agency	Florida DOT	• Operational analysis for limited access facilities. • Capacity analysis of weaving/merging/diverging segments, freeways, and ramps for interchanges. • Capacity analysis and traffic signal optimization for urban arterials.	FDOT Traffic Analysis Handbook [43]
State Agency	Michigan DOT	Operations analysis for freeways and ramps, arterials, transit, and CVs/AVs.	Analysis Procedures Manual: Michigan DOT Vissim Protocol Example files [98]
State Agency	Wisconsin DOT	• Capacity analysis of weaving/merging/diverging segments, freeways, and ramps for interchanges. • Capacity analysis and traffic signal optimization for urban arterials.	• Traffic Operation and Safety Analysis Manual: TEOpS 16-20 [53] • Traffic Analysis Tool Selection: Flow Chart [54]

Entity Type	Entity	Use Case	Link
Consultants	Kimley-Horn, Kittelson & Associates, WSP, etc.	Operations analysis for freeways and ramps, arterials, transit, and CVs/AVs in Virginia.	• Arterial operational analysis [99] • I-395 Shirlington Interchange Improvement Study by WSP [100]

3.7.1.8 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 multiresolution software tool.
- Access to Vissim requires a paid license [101].
- 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 [102].

3.7.2 SimTraffic

3.7.2.1 Tool Description

SimTraffic is a complimentary and compatible microscopic simulation tool for Synchro and is included in the Synchro software suite. It has the capability to model any network that can be analyzed using Synchro and to use SimTraffic for analyses, it is necessary to first create the network using Synchro. After the network has been created in Synchro, SimTraffic can be launched either from within the Synchro interface or as a standalone application [41]. SimTraffic uses a formula in which vehicles maintain a fixed headway behind a leading vehicle. This headway is determined by factors such as speed, driver type, and link headway factor. When the leading vehicle exceeds a speed of 2 ft/s, a "fast following" model is applied. Conversely, a "slow following" model is utilized to track slow or stationary vehicles, or to come to a halt at specified points like stop-bars or mandatory lane change starting points. The gap-acceptance model in based on the length of the turning path and type of desired turn [103]. SimTraffic can model the travel of various road user types (e.g., cars, trucks, buses, pedestrians) through different types of intersections, including signalized and unsignalized ones, arterial networks, and freeway sections. This tool utilizes the vehicle and driver performance characteristics that have been developed by the Federal Highway Administration for traffic modeling purposes [104].

3.7.2.2 Tool Category(ies)

Microscopic Simulation.

3.7.2.3 Primary Purposes/Objectives

SimTraffic is used at the project planning stage to select preferred alternatives and at the project implementation stage to determine roadway and signal impacts. Applications of SimTraffic include arterial traffic signal control coordination and optimization, intersection capacity analysis, and network and system performance evaluation.

3.7.2.4 Scope (including applicable ITS component(s))

SimTraffic is used for link and network (intersections, arterials, and corridors) analysis. This tool is also capable of modeling ITS applications such as adaptive traffic signal control.

3.7.2.5 Data Inputs/Requirements

Data required to perform simulation using SimTraffic include the following:

- Geometric Data: Bus stations, grade, HOV lanes, pavement, curve radius, number of lanes, lane add/drop, lane alignment, lane channelization, lane distribution of entering vehicles, lane width, lane restrictions, etc.
- Travel Demand Data: O-D matrices for different user and vehicle classes, turning movements and maneuvers, etc.
- Driver and Vehicle Characteristics: Driver acceleration/deceleration behavior, vehicle fleet type.
- Pedestrian Data: Number of pedestrians crossing intersections.
- 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.

3.7.2.6 Performance Measures/Outputs

Traffic operations performance measures/outputs generated from SimTraffic simulation include 95th Percentile and Maximum Queue Lengths (ft), Delay (sec), Travel Time (min), Space Mean Speed (mph), v/c Ratio, etc.

3.7.2.7 Known Entities that Use the Tool and Select Use Cases

Table 16. Examples of Known Entities that Use SimTraffic and Select Use Cases

Entity Type	Entity	Use Case	Link
State Agency	Virginia DOT	Intersections, arterials, and corridors analysis.	Traffic Operations and Safety Analysis Manual (TOSAM) - Version 2.0 [41]
State Agency	Florida DOT	• Capacity analysis and traffic signal optimization for urban arterials. • Network and system performance evaluation.	FDOT Traffic Analysis Handbook [43]
State Agency	Wisconsin DOT	Capacity analysis and traffic signal optimization for urban arterials.	• Traffic Operation and Safety Analysis Manual: TEOpS 16-20 [53] • Traffic Analysis Tool Selection: Flow Chart [54]

3.7.2.8 Summary

Key findings from the review of SimTraffic include:

- Its ability to effectively model traffic flow, traffic signal progression, and optimization of traffic signal timing.
- Its ability to analyze intersection operations under heavy congestion.
- Its ability to model networks with signalized and unsignalized intersections.
- SimTraffic does not have the functionality to analyze freeway or interchange systems [41], or model detailed transit operations [105].
- SimTraffic does not have as high fidelity as most other microscopic simulation tools [104].
- Access to SimTraffic requires a paid license, and the tool may require additional training or skills to effectively use it.

3.7.3 Aimsun*

This tool is also discussed the State of Research report.

3.7.3.1 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 [106]. 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 [107] to model large areas while having the ability to examine individual zones with a finer level of detail and fidelity [108]. 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. The capabilities of Aimsun can be extended through its API, scripting, Aimsun Next's vehicle-to-everything (V2X) software development kit (SDK) (utilizing Adaptive Cruise Control and Cooperative Adaptive Cruise Control car-following models), etc. [107]. 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 [109].

3.7.3.2 Tool Category(ies)

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

3.7.3.3 Primary Purposes/Objectives

Aimsun is used for policy and planning modeling (e.g., lane closures, turn closures, speed reductions for traffic calming) multimodal transportation analysis (e.g., vehicles, trains, pedestrians, cyclist), mobility analytics (special event planning and operations), real-time transportation management, demand modeling, estimating the impact of emerging mobility technologies (e.g., electric vehicles, shared automated vehicles, connected vehicles), energy and emissions modeling, and cost-benefit analysis of ITS technologies/strategies [110].

3.7.3.4 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 crossing, emergency vehicle preemption, dynamic speed control, dynamic lane assignment signals, and changeable message signs.

3.7.3.5 Data Inputs/Requirements

Data required to model and simulate 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.
- Driver and Vehicle Characteristics: Driver acceleration/deceleration behavior, vehicle fleet type.
- Pedestrian Data: Number of pedestrians crossing intersections.

3.7.3.6 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. [111].

3.7.3.7 Known Entities that Use the Tool and Select Use Cases

Several cities world-wide have tested and/or adopted Aimsun models including Paris, Abu Dhabi, Toronto, London, and New York [112].

Table 17. Examples of Known Entities that Use Aimsun and Select Use Cases

Entity Type	Entity	Use Case	Link
City	New York City DOT	Urban network congestion management using real-time data for signal control in Midtown Manhattan, New York City, NY.	Manhattan Traffic Model (MTM) [113]
County Agency	San Diego Association of Governments (SANDAG)	Use of real-time modeling for a decision support system as part of the integrated corridor management system (ICMS) along I-15 corridor in San Diego, CA, including the freeway corridors, parallel arterials, and transit operations.	San Diego Interstate 15 ICMS [114]
State Agency	Florida DOT	Use of real-time modeling for a decision support system as part	Central Florida Regional ICMS [115]

Entity Type	Entity	Use Case	Link
		of ICMS along I-4 corridor in Florida, including the freeway corridors, parallel arterials, and transit operations.	
State Agency	Virginia DOT	Analysis of small area networks to evaluate impacts of traveler information and compare alternatives.	Traffic Operations and Safety Analysis Manual (TOSAM) Version 2.0 [41]

3.7.3.8 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 ability to provide decision support for transportation planning and policymaking.
- 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.
- Access to Aimsun requires a paid license and the tool may require additional training or skills to effectively use it.

3.7.4 Paramics*

This tool is also discussed the State of Research report.

3.7.4.1 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 [116]. 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 [117]. Paramics includes multimodality and has the ability to model passenger vehicles, buses, trams, and pedestrians [118]. Paramics is a commercial tool and requires the purchase of a license to use [119].

3.7.4.2 Tool Category(ies)

Microscopic Simulation.

3.7.4.3 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, and others. 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 [118].

3.7.4.4 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.

3.7.4.5 Data Inputs/Requirements

Data required to model and simulate 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.

3.7.4.6 Performance Measures/Outputs

Some of the performance measures/outputs generated from Paramics modelling and simulation include VMT, Vehicle Hours Traveled (VHT), Queue Length, Average Delay (seconds), Density (vehicles/km), Vehicle Throughput (vehicles/hour), Average Speed (km/hour), Average Stops, Average Travel Time (seconds or minutes), Total Time Stopped for Public Transit (seconds or minutes), Passengers Boarding/Alighting, etc. [120].

3.7.4.7 Known Entities that Use the Tool and Select Use Cases

Table 18. Examples of Known Entities that Use Paramics and Select Use Cases

Entity Type	Entity	Use Case	Link
State Agency	New York State Energy Research and Development Authority, New York State DOT	A Paramics simulation-based corridor decision making tool that can help evaluate alternative corridor scenarios based on corridor level mobility, fuel consumption, and emissions.	Simulation-Based Decision Making Tool for Adaptive Traffic Signal Control [121]
State Agency	Mississippi DOT	A Paramics microsimulation model to assess the performance of two roundabouts.	Performance Evaluation of Roundabouts for Traffic Delay and Crash Reductions [122]

3.7.4.8 Summary

Key findings from the review of Paramics include:

- Its ability to perform large-scale microsimulations.
- Its ability to perform economic assessments of improvement projects to aid in decision making.
- Its ability to incorporate pedestrians and bicyclists in modeling and visualization [123].
- It has built-in 3D visualization.
- Paramics has potentially time- and data-intense model development and calibration, depending on the size of network and complexity of scenario [104].
- It does not have the capability to output signal coordination timing [104].
- Outputs and MOEs from Paramics may require post-processing.
- Access to the tool requires a paid license and the tool may require additional training or skills to effectively use it.

3.7.5 CORSIM*

This tool is also discussed the State of Research report.

3.7.5.1 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 [124].

This tool was first sponsored and developed by FHWA. It consists of the integration of two models that are able to 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 [124]. 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 CORSIM. It writes the collected data to an Excel workbook, a comma-separated file, and/or a tab separated file [116]. Overall, CORSIM is a versatile tool that provides transportation planners and engineers with a comprehensive set of modeling capabilities. CORSIM is a commercial tool that requires a paid license to use and is managed by the McTrans Center at the University of Florida [125].

3.7.5.2 Tool Category(ies)

Microscopic Simulation.

3.7.5.3 Primary Purposes/Objectives

CORSIM has been applied by practitioners and researchers worldwide 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, HCS tools, and other algorithms.

3.7.5.4 Scope (including applicable ITS component(s))

CORSIM is used for modeling 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, traffic signal preemption at (or near) railroad crossings, emergency vehicle preemption, incident detection and management, managed lanes such as HOV and HOT lanes, etc.

3.7.5.5 Data Inputs/Requirements

Data required to model and simulate 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.

3.7.5.6 Performance Measures/Outputs

Traffic operations performance measures/outputs generated from CORSIM modelling and simulation 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. [126].

3.7.5.7 Known Entities that Use the Tool and Select Use Cases

Table 19. Examples of Known Entities that Use CORSIM and Select Use Cases

Entity Type	Entity	Use Case	Link
City Agency	Chicago DOT	Traffic signal optimization for an urban roadway network in Chicago, IL.	Traffic Signalization Study – Chicago [127]
State Agency	Florida DOT	Model to assist with the assessment of preliminary engineering, roadway design, traffic system performance, and weaving area and ramp terminal analysis.	FDOT Traffic Analysis Handbook [43]
State Agency	Virginia DOT	Analysis of small area networks to evaluate impacts of traveler information and compare alternatives.	Traffic Operations and Safety Analysis Manual (TOSAM) Version 2.0 [41]

3.7.5.8 Summary

Key findings from the review of CORSIM include:

- Its ability to accommodate time-varying demand and 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 [126].
- Access to CORSIM requires a paid license and the tool may require additional training or skills to effectively use it.

3.7.6 TransModeler*

This tool is also discussed the State of Research report.

3.7.6.1 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. 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 [128]. TransModeler provides a multiresolution hybrid simulation capability in which high fidelity microsimulation can be combined with mesoscopic and macroscopic simulation on any network segments. Specified segments of interest within the network can be simulated with microscopic simulation and other segments or subnetworks can be simulated with lower resolution methods. This hybrid capability makes it possible to simulate very large networks without needing extensive computing power [129]. 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.

3.7.6.2 Tool Category(ies)

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

3.7.6.3 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.

3.7.6.4 Scope (including applicable ITS component(s))

TransModeler can model and simulate links, networks, urban areas, counties, and regions [130]. 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 [131].

3.7.6.5 Data Inputs/Requirements

Data required to model and perform 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.

3.7.6.6 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. [132].

3.7.6.7 Known Entities that Use the Tool and Select Use Cases

Table 20. Examples of Known Entities that Use TransModeler and Select Use Cases

Entity Type	Entity	Use Case	Link
City	Lake County, CA	A 450-square-mile microscopic traffic simulation model spanning most of Lake County, CA used to evaluate traffic demand within the study area.	TransModeler Projects [133]
State Agency	North Carolina DOT	Modeling and simulation of engineering design alternatives and ITS applications to reduce congestion and improve roadway safety on freeway and arterial/local street facilities.	NCDOT Congestion Management Simulation Guidelines - TrasModeler [132]
State Agency	Maryland State Highway Administration	A microscopic simulation model to demonstrate the feasibility and benefits of deploying ICM along the I-270 corridor in Montgomery County, MD.	TransModeler Projects [133]
Consultant	CLR Analytics	A microsimulation model for testing alternative build scenarios under future conditions for the State Route 91 Corridor System Management Plan in Orange County, CA.	TransModeler Projects [133]

3.7.6.8 Summary

Key findings from the review of TransModeler include:

- It has multiresolution hybrid simulation capabilities in which high-fidelity microscopic simulation can be readily 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, and 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 [46].
- 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 [134].
- There is limited access to electronic tool user manuals since they are accessible only when running the tool [134].
- Access to TransModeler requires a paid license, and the tool may require additional training or skills to effectively use it.

3.7.7 TRANSIMS

3.7.7.1 Tool Description

Transportation Analysis and Simulation System (TRANSIMS) is a tool with an integrated set of models, based on cellular automation microscopic simulation, that are used to conduct analysis of regional transportation systems. The simulation of vehicle movement involves transitioning from one cell to another within a time step, with the vehicle's next position determined by a predefined set of driving rules. Vehicle acceleration and deceleration are contingent upon both the vehicle's current velocity and the distance to the vehicle directly in front of it in the same lane [135]. Developed at Los Alamos National Laboratory, this tool uses a modeling archetype of individual travelers that allows for multimodal travel (i.e., a traveler’s journey can be completed by multiple transportation modes). TRANSIMS operates on an activity-based integrated framework that differs from other travel demand forecasting methods in its underlying concepts and structure. These differences include a continuous and consistent representation of time; a detailed representation of persons and households; time-dependent routing; and a person-based microscopic-level simulator [116]. TRANSIMS is an open-source tool and is made available under the NASA Open-Source Agreement Version 1.3.

3.7.7.2 Tool Category(ies)

Microscopic Simulation, Travel Demand Models.

3.7.7.3 Primary Purposes/Objectives

TRANSIMS is an activity-based tool with an integrated system of travel forecasting and microscopic simulation models developed for regional transportation planning. Although TRANSIMS was originally developed for travel demand forecasting, it has been used for different purposes including modeling evacuations, traveler response to tolls, analysis of safety benefits of alternatives, etc. [136].

3.7.7.4 Scope (including applicable ITS component(s))

TRANSIMS can model and simulate large road and transit networks (i.e., over 100,000 links). In addition, it can accommodate more than 30 million travelers. In terms of ITS applications, TRANSIMS has the ability to support modeling of HOT lanes with dynamic pricing component, evacuation, and traffic management under inclement weather conditions [136].

3.7.7.5 Data Inputs/Requirements

Data required to model and perform simulation using TRANSIMS include the following:

- Geometric Data: Lane width, lane length, horizontal and vertical grade, lateral curvature, number of lanes, etc. are all captured in TAZ files.
- Signal Timing Data.
- Traffic Flow/Travel Demand Data: O-D matrices, travel times, travel speeds, transit schedules, transit routes and stops, transit volumes, etc.
- Driver and Vehicle Characteristics: Driver acceleration/deceleration behavior, vehicle fleet type.
- Other Data: Census data, activity survey data, trip table.

3.7.7.6 Performance Measures/Outputs

Some of the key performance measures/outputs at the regional or macroscopic level include VMT, VHT, Total Travel Time, Average Travel Time, and Pollutant Levels. Performance measures/outputs at the microscopic level include Average Travel Time, Average Speed, Vehicle Throughput, and Intersection Measures (e.g., Total Delay, Delays Per Cycle, Number of Stopped Vehicles in Queue, etc.).

3.7.7.7 Known Entities that Use the Tool and Select Use Cases

Table 21. Examples of Known Entities that Use TRANSIMS and Select Use Cases

Entity Type	Entity	Use Case	Link
City	Moreno Valley, CA	A TRANSIMS model to assess proposed land use changes and their impacts on travel. The high-fidelity TRANSIMS model provides insights on operational impacts compared with traditional travel demand models.	Moreno Valley TRANSIMS Traffic Model [137]

3.7.7.8 Summary

Key findings from the review of TRANSIMS include:

- The tool is open-source and does not require a paid license to access.
- Its ability to support large-scale microscopic simulations, enabling the evaluation of strategy impacts at the tactical/local level through the system-wide level for large road and transit networks, accommodating large populations.
- TRANSIMS requires significant Central Processing Unit (CPU) time and extensive storage capacity. [138]
- Since it is an open-source tool, there is limited technical support available to users.

3.7.8 SUMO*

This tool is also discussed the State of Research 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 readily implementable and include strategic, cooperative, tactical, and regulatory. [139] 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. Such contributions made available through the SUMO website, however they are not verified before being released and potential users are responsible for their own testing [140].

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., V2X communications). This is done by coupling SUMO to a communication network using a middleware (e.g., Veins, iCS, MOSAIC) [141].

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 simulate 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. [142].

3.7.8.7 Known Entities that Use the Tool and Select Use Cases

Table 22. Examples of Known Entities that Use SUMO and Select Use Cases

Entity Type	Entity	Use Case	Link
State Agency	Kansas DOT	A microsimulation model to detect and quickly respond to highway incidents to mitigate traffic flow breakdown in Wichita, KS.	Intelligent Highway Management System for the City of Wichita [143]

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.
- 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.
- Since it is an open-source tool, there is limited technical support available to users.

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 typically used in practice scope of this report. These include:

- Motor Vehicle Emissions Simulator (MOVES)
- Surrogate Safety Assessment Model (SSAM)

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

3.8.1 Motor Vehicle Emissions Simulator

3.8.1.1 Tool Description

Motor Vehicle Emissions Simulator (MOVES) is a state-of-the-science model designed by the U.S. Environmental Protection Agency (EPA) that is used to estimate air pollution emissions from mobile sources in the United States. This tool estimates emissions for mobile sources at the national, county, and project level for standard air pollutants, greenhouse gases, and air toxins [144]. The mobile sources include combustion products (e.g., running exhaust), hydrocarbon evaporation (e.g., resting loss) and others (e.g., brake wear) [145]. MOVES3 is the latest official version of the tool and has been updated and improved from the previous version by incorporating the latest data on vehicle populations, travel activity, and emission rates; adjusting the modeling to better account for vehicle starts, long-haul truck hoteling, and off-network idling; and incorporating impacts of the Heavy-Duty Vehicles Greenhouse Gas Rule Phase 2 as well as the Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule. These updates ensure that MOVES3 is the most accurate tool for estimating emissions from the transportation sector for the majority of scenarios [144]. In MOVES3, emissions estimation is performed using an analytical approach. The user can choose between two calculation types, inventory or emission rates. Opting for inventory yields emission estimates in mass, based on user-input VMT and vehicle population. On the other hand, selecting emission rates provides emission rates measured in mass per unit of activity. To construct an emission inventory using rates, running rates are applied to VMT. Emissions resulting from activities during vehicle parking, such as start, evaporative, and extended idling rates, are scaled by the overall vehicle population within the area of interest. Off-network idling rates are computed by multiplying the rate by the number of hours dedicated to off-network idling [146].

3.8.1.2 Tool Category(ies)

Other – Emissions Analytical Tool.

3.8.1.3 Primary Purpose(s)/Objective(s)

MOVES can be used to estimate exhaust and evaporative emissions as well as brake and tire wear emissions from all types of vehicles on a roadway. MOVES can also be used to estimate emissions from many kinds of non-road equipment. The on-road and non-road modeling capabilities exist as separate modules in MOVES.

3.8.1.4 Scope (including applicable ITS component(s))

MOVES can estimate emissions at the corridor/intersection level, traffic analysis zone level, or the national level. For ITS roadway environmental monitoring applications implemented at the corridor/intersection level, MOVES can use simulated vehicle trajectories to estimate emissions [147].

3.8.1.5 Fidelity and/or Resolution

MOVES uses the varying levels of detail to estimate emissions at the national (high-level, low fidelity), traffic analysis zone (medium-level, medium fidelity), and corridor/intersection/link (fine-level, high fidelity) levels.

3.8.1.6 Data Inputs/Requirements

The input data required for MOVES include VMT by vehicle type, the number of each type of vehicle, vehicle age distributions, fuel information (i.e., fuel supply, fuel formulation, fuel usage fraction, etc.), meteorological data, road type distribution, retrofit data, average speed distribution, etc. [148].

3.8.1.7 Performance Measures/Outputs

Emission estimates from MOVES include Nitrous Oxide (N_2O), Primary Exhaust PM2.5-Total, Primary Exhaust PM10-Total, Primary PM2.5 – Brake Wear Particulate, Sulfur Dioxide (SO_2), Total Energy Consumption, etc. [144].

3.8.1.8 Known Entities that Use the Tool and Select Use Cases

Table 23. Examples of Known Entities that Use MOVES and Select Use Cases

Entity Type	Entity	Use Case	Link
City	Houston, TX	The Texas Transportation Institute estimated emissions from trucks at the Port of Houston using the MOVES tool to support transportation and air quality planning.	Houston-Galveston Area Air Quality Planning [149]
Federal	Volpe	Modeling of automated vehicle behavior in microsimulation tools and feeding simulated vehicle trajectories into MOVES for emissions estimation.	Energy and Emissions Benefits for CAVs [150]

3.8.1.9 Summary

Key findings from the review of MOVES include:

- The tool is open-source and does not require a paid license to access.
- Its ability to estimate emissions at different scales depending on use case [147].
- It requires detailed knowledge of Excel and the Visual Basic programming tool [151].
- Feeding simulated vehicle trajectories as input to MOVES requires conversion from simulation file format to the MOVES file format. This conversion process may require additional skills/training to complete.
- Since it is an open-source tool, there is limited technical support available to users.

3.8.2 Surrogate Safety Assessment Model

3.8.2.1 Tool Description

The Surrogate Safety Assessment Model (SSAM) is a software tool developed to automatically identify, classify, and evaluate traffic conflicts in vehicle trajectory data output from microscopic traffic simulation models. SSAM also has built-in statistical analysis features for determining conflict frequency and severity measures that can aid analysts in the design of safe traffic facilities. SSAM analyzes vehicle trajectory data using a series of computational algorithms which determine conflict points, conflict lines from vehicles merging into the same lane, and conflict lines for vehicles following one another in the same lane. The computational algorithms consider the vehicle speed, location, and acceleration as well as driver behavior parameters. This tool addresses limitations in the use of police crash reports for safety analysis. The current version of SSAM (version 3.0), improves software performance and adds the capability of differentiating between at grade and grade-separated conflicts at interchanges. The SSAM software development was sponsored by FHWA and is available freely to the public [152].

3.8.2.2 Tool Category(ies)

Other – Safety Analysis Tool.

3.8.2.3 Primary Purpose(s)/Objective(s)

The primary purpose of SSAM is to automatically identify, classify, and evaluate traffic conflicts in the vehicle trajectory data output from microscopic traffic simulation models [152].

3.8.2.4 Scope (including applicable ITS component(s))

SSAM is able to identify traffic conflicts on all types of road facilities. For ITS applications implemented in microscopic simulation tools, SSAM is able to identify and evaluate traffic conflicts based on simulated vehicle trajectories [152].

3.8.2.5 Fidelity and/or Resolution

The SSAM tool uses vehicle trajectory data output from high-fidelity microscopic traffic simulation models to identify traffic conflicts [153].

3.8.2.6 Data Inputs/Requirements

Input data required for the SSAM tool include Vehicle Trajectory Data and threshold values for Time-to-Collision (TTC) and Post-Encroachment Time (PET) [153].

3.8.2.7 Performance Measures/Outputs

The SSAM tool does not generate performance measures. Instead, threshold values from two performance measures, TTC and PET, are used as inputs to identify traffic conflicts. Outputs include conflict counts and conflict events, which can also be categorized based on the type of driving maneuver (crossing, rear-end, and lane-change events) [153].

3.8.2.8 Known Entities that Use the Tool and Select Use Cases

Table 24. Examples of Known Entities that Use SSAM and Select Use Cases

Entity Type	Entity	Use Case	Link
State Agency	Utah DOT	Investigation of the effectiveness of using the SSAM to evaluate highway or intersection safety, particularly	Assessing Safety Impacts of Access Management Alternatives Using SSAM [154]

Entity Type	Entity	Use Case	Link
		the safety effects of multiple access management alternatives.	

3.8.2.9 *Summary*

Key findings from the review of SSAM include [152]:

- The tool is open-source and does not require a paid license to access.
- It addresses limitations in basing safety analysis on police-reported crash reports, which is often too slow to reveal the need for remediation.
- SSAM is supported by multiple commonly used microscopic simulation tools.
- SSAM requires a rigorous calibration procedure be applied to the microscopic simulation model whose output vehicle trajectories will be inputs to the tool in order to generate reliable conflict results [155].
- There is a possibility that the tool produces unreliable conflict results since simulation models may not accurately represent actual driving behavior and often fail to capture the actual mechanisms generating near-misses [155].
- SSAM may require additional training and skills to effectively use the tool.
- Since it is an open-source tool, there is limited technical support available to users.

3.9 AMS for ITS Tools Literature Review Summary

AMS is a core competency in the field of transportation engineering. Transportation agencies continuously rely on AMS tools to understand prevailing safety, mobility, and other issues as well as test and compare corresponding mitigating strategies and impacts of technology prior to field deployment as well as to evaluate them during deployment. A comprehensive review of literature on AMS for ITS tools that are used in practice by agencies and practitioners was conducted as part of this effort. Note, however, that an exhaustive review was not feasible. **Table 26** in **Appendix A** presents a consolidated list of the 22 identified AMS for ITS tools typically used in practice by primary TAT category type. The following is a summary of key findings from the literature review.

- **AMS for ITS tools have varying levels of fidelity and resolution –** There is a variety of AMS tools for ITS being used by transportation agencies to satisfy various transportation needs. Ranging from simple, low resolution and fidelity analytical/deterministic tools to sophisticated high resolution and fidelity micro-level tools, each tool offers unique capabilities that can be leveraged by agencies to diagnose, plan, and improve their transportation system. Low resolution and fidelity tools are typically much faster and have fewer data/computational capability requirements to implement than high resolution and fidelity tools.

- **Capabilities of AMS for ITS tools can be extended –** Most of the AMS for ITS tools reviewed provide opportunities for their capabilities to be extended through multiple means including APIs, SDKs, or other interfaces.
- **Commercial AMS for ITS tools are more prevalent than open-source tools –** Most of the AMS for ITS tools reviewed are developed by private companies and require a paid license/subscription to access them. The open-source tools are mostly sponsored by public agencies. In terms of documentation and technical support, the commercial AMS for ITS tools tend to have more documented resources and available technical support than open-source tools.
- **Few AMS for ITS tools have MRM capabilities –** Most of the AMS for ITS tools reviewed either do not have the capability to perform MRM, or those capabilities are not typically used in practice. The AMS for ITS tools that do have MRM capabilities are typically those developed by the same company but at different scales. These include Vissim/Visum (micro-travel demand modeling/macro simulation), TransModeler/TransCAD (micro-travel demand modeling/macro simulation), and CUBE/Dynameq (travel demand modeling-meso simulation). However, several of these and other tools include MRM capabilities on their own (e.g., Aimsun with micro-meso and meso-macro simulation).
- **Most of the AMS tools that incorporate ITS components fall within the microscopic simulation category –** The most prevalent principal category of AMS for ITS tools used in practice is microscopic simulation. The categories with the next most tools are travel demand models and mesoscopic simulation. Note that the macroscopic simulation tools do not directly model ITS applications. However, they can be integrated with mesoscopic and microscopic tools to assess system-wide impacts of ITS applications, strategies, and/or technology components.
- **Graphical user interface is critical to adoption and use of AMS for ITS tools –** The graphical user interface is an important aspect of AMS for ITS tools per the literature reviewed. A well-designed graphical user interface facilitates straightforward, easy building of the modeling and/or simulation network and analyzing/visualizing of results. This reduces the time and effort needed for new and existing users to utilize the tool and influences the decision for agencies to adopt a tool.
- **Few AMS for ITS tools have real-time/predictive capabilities –** All the analytical/deterministic, travel demand models, and macroscopic simulation tools reviewed are typically used offline for planning purposes. Only a few mesoscopic tools (e.g., DYNASMART-X) and microscopic tools (e.g., Aimsun) can be used in online mode to predict future traffic conditions in real-time.
- **Limited safety analysis-specific tools –** Most of the AMS for ITS tools used in practice reviewed mainly focus on mobility and transportation planning. Only the SSAM tool focuses on safety by identifying traffic conflicts based on outputs from microscopic simulation tools.
- **Some microscopic simulation AMS for ITS tools can model large-size networks** – Microscopic tools are often limited in terms of the size of networks they can model because of the amount of detail needed in modeling and corresponding computational burdens. Notwithstanding, there are a few microscopic simulation AMS for ITS tools that are able to

model and simulate large-size networks such as cities (e.g., TransModeler, Aimsun, and TRANSIMS).

- **ITS emerging technologies and new data modeled at the microscopic and mesoscopic levels** – The impacts of emerging technologies such as CAVs are mostly modeled using microscopic and mesoscopic tools. Per the literature reviewed, macroscopic and other higher-level tools (e.g., travel demand models, analytical/deterministic) have not been used to assess the impacts of emerging ITS technologies and their new data.

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

Artificial intelligence/machine learning have the potential to improve the existing analysis, modeling, and simulation capabilities being leveraged by transportation professionals. AI/ML algorithms such as support vector machines (SVM) and long short-term memory (LSTM) neural networks can be used to predict travel times. Similarly, k-nearest neighbor (KNN) clustering and decision tree techniques for classification and regression purposes can be used to predict and possibly help prevent or mitigate collision occurrences [156]. Although research on how to incorporate AI/ML techniques into transportation modeling has been ongoing for a while, most of the AMS for ITS tools that are typically used in practice do not utilize these techniques. However, there are a few tools such as Aimsun which combines AI/ML techniques with high-speed simulations to predict future traffic conditions based on which appropriate mitigation strategies can be implemented [157]. Per the literature reviewed, these capabilities are mainly used in pilot projects and rarely used in daily management of traffic or for other state of practice objectives.

Adoption of AI/ML-enhanced AMS tools by agencies may be slow for several reasons. One of the challenges is the maturity level of AI/ML-based techniques. Transportation agencies will only adopt these techniques if they prove to be reliable and trustworthy in terms of their accuracy and ability to improve existing tools being used. Tool developers are still working on making these techniques mature by collecting large datasets to train, test, and validate their AI/ML algorithms. Interpretability of results also remains a challenge, which is a particular concern for safety-critical transportation applications in which it may be imperative but also difficult to reconstruct why a collision or incident occurred. In addition, the cost of acquiring AI/ML-enhanced AMS tools can be a deterrent to agencies since they need to justify their request to acquire new or updated tools and show a business case to secure funds.

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

Per a review of publicly available literature, it was established that most agencies do not have rigorous capability maturity models and technology readiness frameworks when it comes to AMS for ITS tools. The following are key findings on the use of capability maturity models and technology readiness levels as they pertain to AMS for ITS tools:

- FHWA's Traffic Analysis Capability Maturity Framework provides guidance on a structured approach to identify traffic analysis/AMS capabilities and technology readiness level. However, there is no publicly available evidence of its usage by agencies [158]. Publications on how agencies have used this framework are forthcoming.
- Many agencies have guidance documents and/or tools to help their practitioners select the right AMS tool based on different operational conditions (e.g., saturated vs. unsaturated) and other project-specific characteristics. For example, Virginia Department of Transportation (VDOT) has guidance tables and uses its Software Selection Tool (SST) to select AMS tools [41], Ohio [159] Department of Transportation (ODOT) has guidance documentation to select appropriate tools, and the Kentucky Transportation Cabinet uses its Traffic Analysis Software Selection Tool for selecting appropriate tools [160].
- Some agencies only provide a list of approved AMS tools without providing detailed guidance on operational conditions governing their usage. New York State Department of Transportation (NYSDOT) is an example of such agencies [161].
- Consequently, there is a need to engage agencies to learn about internal processes regarding the assessment of AMS for ITS tools' capability maturity and technology readiness level frameworks.

4 Stakeholder Feedback

A volunteer group of expert stakeholders was established from representatives of state, local, and regional agencies and consultants who are practitioners and tool developers in the area of AMS for ITS tools. The ITS JPO's AMS for ITS 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 used in typical practice, specifically regarding what tools they use, how they use them, and what they think are the limitations of these tools (if any). Discussions were held with a total of twelve stakeholders from eight organizations, including three state DOTs, two consulting firms, and three tool development vendors. The two interview questionnaires, one for practitioners and one for tool developers, 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

- Tools that the interviewed practitioners use for a variety of ITS analysis, modeling, and/or simulation purposes are listed below. These tools are also included in the literature review.
  - Vissim for analysis/modeling of emerging mobility and technologies, multimodal transportation planning, micro-level modeling.
  - Visum for planning related to emerging technologies and travel demand modeling.
  - Vistro for transportation network and system optimization, traffic impact assessment
  - Aimsun for multimodal transportation planning.
  - Synchro for transportation network and system optimization, traffic signal optimization.
  - Sidra Intersection for traffic signal optimization.
  - TransModeler for multimodal transportation planning, microscopic simulation, mesoscopic simulation, and hybrid multiresolution simulation.
  - Dynameq for mesoscopic and microscopic traffic simulation.
  - MOVES for macro-level transportation conformity and other environmental analysis.
  - HSM software for safety analysis at the micro-level.
  - TransCAD software for macro-level travel demand analysis and forecasting/planning, some multiresolution modeling.
- Additional AMS tools that the interviewees identified are listed below. These tools are considered out of scope of this report and not expanded upon further in the literature review

because they either do not include at least one component of ITS or they are not considered part of typical practice.

  - Tru-Traffic for corridor signal offset optimization.
  - DTALite for meso-level modeling.
  - Interchange Safety Analysis Tool Enhanced (ISATe) for traffic safety analysis/modeling.
  - Interactive Highway Safety Design Model (IHSDM) for traffic safety analysis/modeling.

- Some agencies also mentioned use of in-house developed software (e.g., Texas DOT's TexPACK for macro-level travel demand analysis in urban areas and Statewide Analysis Model [SAM] for macro-level travel demand analysis that incorporates freight and passenger vehicle components).
- Most software tools are not open-source and require a paid license and/or subscription to access, which limits the number and breadth of tools practitioners working for resource-constrained agencies are able to utilize.
- When selecting what tools to use, agencies indicated that they do not use Capability Maturity Models or Technology Readiness Levels in the traditional sense, but several agencies indicated that they do have Standard Operating Procedures (SOPs) in place to help them down-filter what tools to use for what projects. For example, Virginia DOT uses Traffic Operations And Safety Analysis Manual (TOSAM) [41] and Texas DOT uses Traffic Safety and Operations Manual (TSOP) (currently in the process of being published). Factors such as end goal(s) of a project, saturation level, typical traffic conditions, network size, need for visualization, etc. are utilized to select tools in Virginia DOT's TOSAM [41]. There was a general tendency to use the tools that an agency already has access to (licensing) and is familiar with.
- Models that are relatively new and/or under development that are anticipated by practitioners and/or tool vendors to be impactful in the near future are:
  - Trans Intelligence's TranSync for systematic real-time management, optimization, and performance analysis of traffic signal timing plans.
  - 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.
  - Aimsun's Aimsun Next for multiresolution (e.g., hybrid macro-meso and meso-micro) traffic modeling.

4.2 Applicable Use Cases

- Agencies expressed the importance of using AMS for informing decision makers about ITS strategies, including the role models play in justifying proposed changes in access to the Interstate System (as required by FHWA's Interstate Access Policy) [162].
- Agencies reported performing traffic modeling at macroscopic, mesoscopic, and microscopic resolutions and are increasingly performing more multiresolution modeling. A few agencies

indicated that they would like to get more into multiresolution modeling, but that they are currently hindered by budget, staffing, training, etc. resource constraints.

- Some agencies mentioned performing time-dependent/variant or dynamic modeling analysis to assess the impacts of potential congestion mitigation and corridor improvement projects (e.g., ramp metering solutions, hard shoulder running, variable speed limits), while others indicated they do not currently perform dynamic modeling but have plans to in the future. Additionally, while some practitioners noted that they perform activity or agent-based modeling to assess multimodal systems, such as with bus rapid transit (BRT), others noted resource constraints prevent them from doing so.
- Performance measures most often considered include mobility indicators such as queue length, delays, VHT, travel times, speeds, flow (LOS), 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. Safety measures were largely absent from the discussions (see crash analysis under "Limitations, Gaps, and Challenges"). Automated Traffic Signal Performance Measures (ATSPM) [163], which focus on targeted traffic signal maintenance and improving operations and increasing safety through re-timing, were noted as being more recent additions to the above listed measures agencies determine and utilize for decision making.
    - Some agencies are beginning to utilize machine learning algorithms for setting targets for performance measures.

4.3 Input/Calibration Data

- Many practitioners indicated they still rely on collecting their own field data from traditional ITS data sources, such as loop detectors and microwave sensors. At the same time, many agencies are looking ahead to emerging data sources, such as data collected from mobile devices serving as vehicle "probes". Feedback suggests that volume data, in particular, has become increasingly difficult to collect, especially since the COVID-19 pandemic. Interviewees reported supplementing field data with the following data from other sources, including:
    - Open-source Data: Agencies reported using OpenStreetMap and Google Earth for geometric data, 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.
    - Proprietary Data: Agencies reported purchasing INRIX data (travel time, speeds, bottleneck locations, congestion scans, etc.) whenever they have the means to, noting that this data is sampled from the whole and is not representative of the local population being modeled. Additionally, some agencies also utilize services/software such as Miovision that help convert video data into count data. At least one agency also indicated that they were experimenting with using vehicle trajectory data from Wejo. One

practitioner noted their use of StreetLight data for operations studies and to understand routing and traffic patterns. Additionally, one agency noted that they share their ITS-infrastructure data with Waze and use TomTom probe data to help fill gaps.

4.4 Limitations, Gaps, and Challenges

- Interviewees noted an overall gap between research and application. Though many agencies are able to glean great theoretical modeling and simulation insight through partnerships with universities, there exist two critical issues: 1) academic researchers often lack real-world experience, so the most robust AMS research tools they develop do not meet the needs of practitioners; and 2) there is a lack of direction from agencies and/or U.S. DOT in how to apply these robust methods and tools to the real-world.
- Other shortfalls noted include particular use cases that current AMS tools do not explicitly support, such as two-way left turn lanes and traffic crash analysis (crash probabilities, crash predictions, near-miss analysis).
- Practitioners cited clunky user interfaces as difficult to maneuver, and expressed desire in interfaces that were overall more user-friendly. Additionally, agencies agreed that they would like to see tools have more built-in knowledge of components such as geometry data and HCM values.
- Some interviewees remarked that constant software versioning introduces compatibility issues and reduces overall credibility of the tools. As release notes do not always specify everything that was changed with each new release, it can be extremely difficult to compare measures of effectiveness between software versions.
- Additionally, lack of funding for new tools, workforce training for new tools, enhanced computational capabilities to support new/enhanced tools, etc. along with return-on-investment analysis to help provide support to obtain additional funding for new and/or updated AMS tools was noted by several agencies.
- There was general consensus that there is a lack of empirical driver behavior data (e.g., regarding lane-changing, speed compliance, route choice, and how drivers react to and interact with emerging ITS, etc.). This makes it particularly difficult to model advanced ITS, such as CAVs, where models are heavily based on underlying assumptions.
- Additionally, there was agreement that current AMS tools have limited capabilities for modeling shared mobility and micro-mobility. Current measures are limited to vehicular data and are not readily able to include the optimization of pedestrians, bicyclists, and other micro-mobility specific measures either at all or within the same analysis, modeling, and/or simulation. Shared mobility and micro-mobility introduce the need for additional data, computations, and mathematical models.
- Some agencies noted there can be an overload of data as new data become available as well as uncertainty in how to process and/or incorporate different types of data into their AMS tools.
- Furthermore, several practitioners conveyed that data standards and adoption of the standards are important to be able to use emerging ITS data in AMS tools. Lack of adoption/implementation or participation with these standards can lead to AMS tools not

having enough transparency and/or being contradictory to each other when incorporating ITS components.

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

This chapter summarizes gaps and challenges in AMS for ITS tools typically used in practice 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 [164] 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 25**. 15 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 25. Summary of Identified Gaps and Challenges in AMS for ITS Tools Used in Practice 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.	Tool license/ subscription cost	Tool License/subscription cost	Literature: CUBE, TransCAD, EMME, Visum, HCS, Sidra Intersection, Synchro, Vistro, DynusT, Dynameq, Vissim, SimTraffic, CORSIM, Dynameq, Paramics, Aimsun, TransModeler; and Interviews	• Adding further grants that provide the needed funding to agencies would lead to broader access to a variety of tools practitioners might not have the funds to obtain otherwise. • More consistent adoption of tested and verified tools to improve agencies' capabilities across a variety of AMS for ITS objective areas.	• Need for ITS JPO to show impartiality towards the vendors developing and licensing these tools. • Cost for providing agencies with license(s)/subscription(s) for vendor-developed software.
2.	Training resource limitations due to extensive required training	Extensive programming/ coding/ tool software workforce training/ development required for standard and/or advanced tool use	Literature: CUBE, TransCAD, EMME, Visum, Vissim, DYNASMART, DynusT, Dynameq, Aimsun, Paramics, TransModeler, TRANSIMS, SUMO, MOVES; and Interviews	• Better understanding of the workforce needs to use a broad spectrum of AMS for ITS tools. • Accessible training that may be tool-specific and/or for cross-tool applicable skills. • Ability for practitioners and agencies with less funding to be able to utilize AMS for ITS tools they would not	• Cost for developing workforce training and/or courses and updating them as advances and new software and versions are created. • Breadth of tools used in practice is vast, presenting difficulty in providing training and/or courses that adequately meet agency/practitioner needs. • Retention after training still an issue.

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
				otherwise have been able to use.	
3.	Extensive time/effort for calibration	Extensive time and effort required for direct (the tool itself) or indirect (another tool used to generate input data for the tool of interest) tool calibration	Literature: Applicable to all microscopic simulation tools (e.g., Paramics, TransModeler, SUMO) as well as SSAM	• If streamlined guidance and training could be provided for common use cases, fewer resources may need to be dedicated to tool calibration. • Expanded use of higher fidelity tools that are considered less accessible due to calibration requirements.	• Cost to update current guidance and/or develop new guidance, and making further updates as new enhancements are created. • Cost to create training and/or course to assist practitioners and agencies in their tool calibration efforts. • Breadth of tools used in practice is vast, presenting difficulty in providing relevant tool calibration guidance, training, and/or courses that adequately meet agency/practitioner needs.
4.	Lack of evidence/methods to make a business case for AMS for ITS tool investments (e.g., ROI)	Lack of ROI analysis and/or guidance for how and when AMS for ITS tools allow for improved practitioner capabilities and support for the various costs associated with	Interviews	• Ability for agencies to justify funding requests for new and/or enhanced AMS for ITS tools, trainings, needed data, etc. • Accessible ROI analysis guidance that may be customized based on agency needs.	• Cost of developing a customizable ROI guide to support acquisition of new and/or updated tools. • Difficulty in adequately accounting for the broad range of tools and use cases that may be of interest to agencies and practitioners.

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
		investing in new tools			• Federal leadership may not support investments in AMS tools.
5.	Need for additional tool output post-processing capabilities	Tool outputs and measures of effectiveness (MOE) may require post-processing for usability	Literature: Paramics, TransModeler	• More streamlined tool output data post-processing that produces useable MOEs for the few/select tools and/or agencies that are lacking them. • Ability for agencies to use tool outputs they may not have been able to previously.	• Cost of developing guidance and/or an additional tool to convert tool output into usable information. • Breadth of tools used in practice is vast, presenting difficulty in providing relevant guidance and/or a tool that adequately meet agency/practitioner post-processing needs. • Significant resources needed to analyze outputs from many tools.
6.	Significant input data requirements	Significant input data amount requirements	Literature: Applicable to most microscopic simulation tools, including Vissim and TRANSIMS	• Access to large amounts of a variety of input data that agencies might otherwise not be able to easily obtain. • Expanded use of the most data-intensive AMS for ITS tools.	• 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.
7.	Significant hardware and storage requirements	Significant CPU/GPU and storage requirements	Literature: TRANSIMS; and Interviews	• Access to online storage and computational platforms could expand access and use of high fidelity and robust ITS for AMS tools.	• Cost for providing secure online storage. • Cost for hosting, maintaining, and supporting a secure online computational platform.

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
		needed to run AMS tools		• Broader adoption of higher fidelity and more enhanced tools in practice.	
8.	Limited interfaces, visualizations, and illustrative capabilities	Limitations with tool user interface, visualization functionalities, and illustrative capabilities	Literature: FREEVAL, HCS, 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.
9.	Limitations with tool collaboration and/or technical support functionalities	Limitations with tool collaboration and/or technical support functionalities	Literature: Aimsun, TransModeler, TRANSIMS; and Interviews	• Increased ability to work within tool modules and/or across various tools for better functionality. • Streamlined technical support, particularly for open-source AMS for ITS tools, so questions are addressed, and tool enhancements are made more rapidly.	• Cost for enhancing tool collaboration capabilities. • Cost for providing further technical support. • Breadth of tools used in practice is vast, presenting difficulty in providing support that adequately meet agency/practitioner needs.
10.	Tool scope limitations	Tool scope limitations (e.g., facility types, lane designation types, transit modes,	Literature: CORSIM, Dynameq, DynusT, DYNASMART, SimTraffic, Visum, Vistro, Synchro,	• Continuously updated guidance, training, and/or use cases for which tools are best applicable for which scenarios could increase understanding	• Cost for developing guidance and/or training and updating them as advances are made and new/updated software are created.

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
		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.)	Sidra Intersection, HCS; and Interviews	and appropriate tool use, and more focused tool developments. • More accurate incorporation of collision 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.	• 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 developing, enhancing, and licensing these tools.
11.	Tool reliability limitations	Tool reliability limitations (e.g., in oversaturated conditions, on low-volume roadways, on facilities larger than specified sizes, credibility issues with	Literature: SSAM, StreetLight, FREEVAL, Synchro; and Interviews	• Better ability to document applicable tool use cases based on calibration and compare against validation data. • Enhanced tracking of tool versioning and backwards compatibility implications.	• Cost to develop and continuously update templates, guidance, and/or training for best practices in documenting tool assumptions, calibration, and validation efforts, etc. • Cost to assist in tracking and documenting tool version updates and backwards compatibility. • Need for ITS JPO to show

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
		constant software versioning and subsequent compatibility issues etc.)			impartiality towards the vendors developing and licensing these tools. • Hard to compare results of different tools using different inputs. • Significant resources required for benchmarking and quality assurance (QA)/quality control (QC) needs.
12.	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	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
		(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).			
13.	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	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	• 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

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
		their AMS tools; lack of enough standards and engagement with standards for ITS data		reliability of AMS for ITS tool outputs.	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.
14.	Tool transparency and interpretability issues related to properly incorporating assumptions and "black box" components	Assumptions and “black box” components of the ITS components within AMS tools can lead to lack of transparency and/or contradictory outputs	Interviews	• Common understanding of best practices and implications of various assumptions to reduce inappropriate conclusions/actions • Increased transparency regarding AMS for ITS tool inputs, processing, and outputs. • More appropriate use of the results of AMS for ITS tools at the agency level, leading to increased trust in AMS for ITS tools.	• Cost to develop and update best practices for presenting tool assumptions. • Difficulty in requesting vendors to increase transparency for their proprietary software. • 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.
15.	Gap in knowledge transfer between	Gap in transferring knowledge to practitioners to	Interviews	• Streamlined process/guidelines for the steps and scenario/use case applications needed to transition AMS for ITS tools	• 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.

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
	research and practice application	promote adoption of new methods and approaches. Practitioners often do not have the means or examples to be able to apply and/or know when to apply the most robust AMS for ITS research tools to consistent real-world scenarios/use cases.		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. • Faster adoption of new and enhanced AMS for ITS tools in practice. • Improved AMS for ITS tool functionalities.	• 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. • 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.

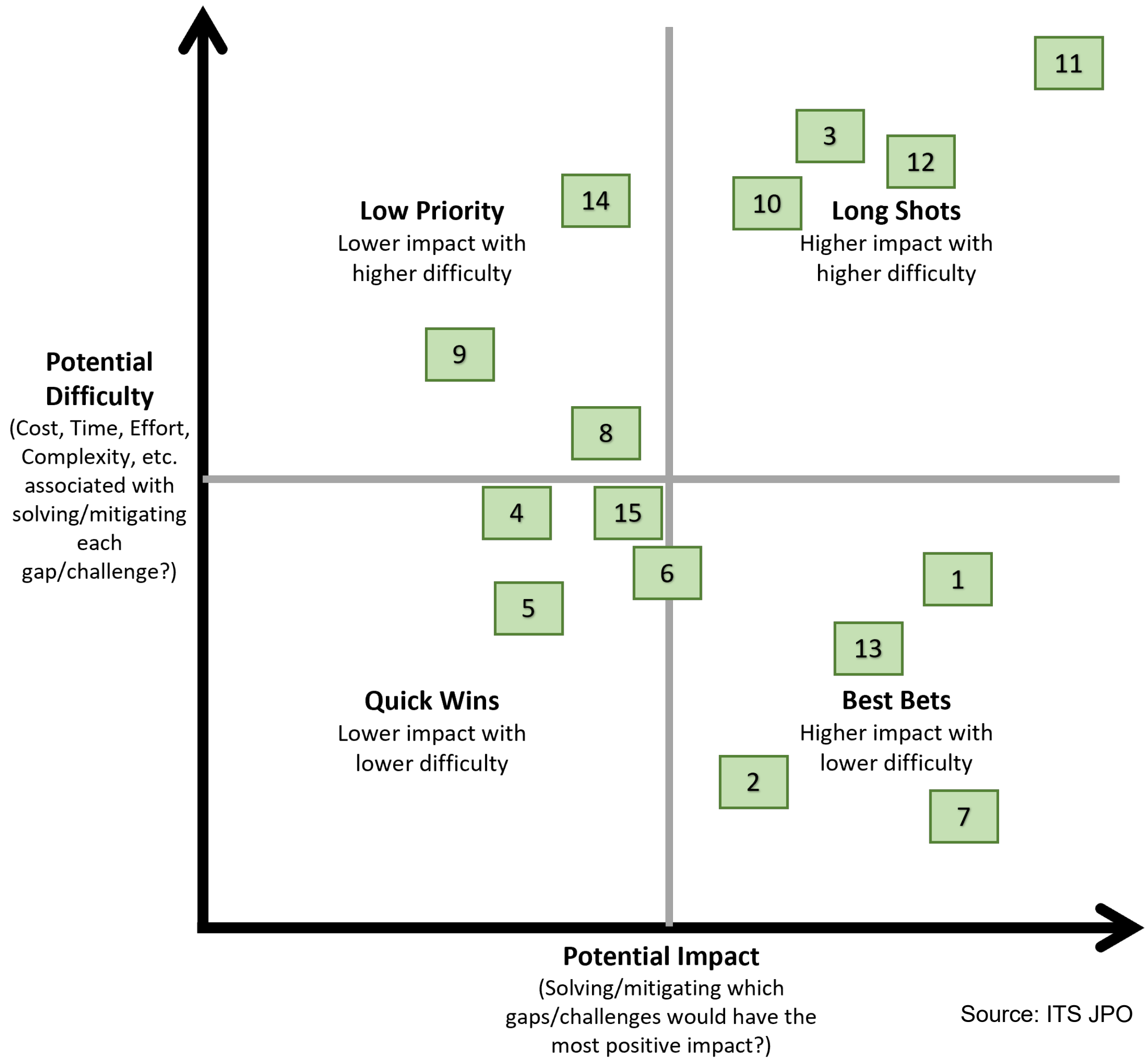

Figure 1. Analysis of Potential Difficulties vs. Impacts for the ITS JPO's AMS for ITS Program to Address the Identified Gaps and Challenges

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 1:** Tool license/subscription cost.
  - **Gap/Challenge 2:** Extensive programming/ coding/ tool software workforce training/ development required for standard and/or advanced tool use.
  - **Gap/Challenge 6:** Significant input data amount requirements.
  - **Gap/Challenge 7:** Significant CPU/GPU and storage requirements needed to run AMS tools.
  - **Gap/Challenge 13:** 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.
- **Potential Quick Wins** (lower impact with lower difficulty)
  - **Gap/Challenge 4:** Lack of ROI analysis and/or guidance for how and when AMS for ITS tools allow for improved practitioner capabilities and support for the various costs associated with investing in new tools.
  - **Gap/Challenge 5:** Tool outputs and measures of effectiveness (MOE) may require post-processing for usability.
  - **Gap/Challenge 15:** Gap in transferring knowledge to practitioners to promote adoption of new methods and approaches. Practitioners often do not have the means or examples to be able to apply and/or know when to apply the most robust AMS for ITS research tools to consistent real-world scenarios/use cases. Lack of guidance for how to promote and facilitate adoption of research-developed AMS for ITS tools and methods with state agencies and practitioners.

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 3:** Extensive time and effort required for direct (the tool itself) or indirect (another tool used to generate input data for the tool of interest) tool calibration.
  - **Gap/Challenge 10:** 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 11:** 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.).
  - **Gap/Challenge 12:** 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).

- **Low Priority** (lower impact with higher difficulty)
  - **Gap/Challenge 8:** Limitations with tool user interface, visualization functionalities, and illustrative capabilities.
  - **Gap/Challenge 9:** Limitations with tool collaboration and/or technical support functionalities.
  - **Gap/Challenge 14:** Assumptions and "black box" components of the ITS components within AMS tools can lead to lack of transparency and/or contradictory outputs.

6 Conclusions

This chapter summarizes key findings from the conducted literature review that identified AMS for ITS tools used in typical practice along with the discussions held with a volunteer group of expert stakeholders from state, local, and regional agencies and consultants, and vendors. It is important to note that an exhaustive survey of all relevant tools used in practice and practitioner entities was not feasible, but this report instead aims to cover a set of tools and entities representative of the state of practice 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 Research 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 Typically Used in Practice from the Literature Review and Stakeholder Interviews

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 typical practice are included in this report. At total of 22 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 the tool and select use cases; and a summary of key findings from the review of the tool, including strengths and gaps/challenges in regard to practitioner 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 26 in Appendix A provides a summary table of the tools. Additionally, interviews were conducted with 12 stakeholders representing 8 organizations ranging from public transportation agencies to consultants to tool developers. Most tools that the practitioners 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 have not yet been adopted more prevalently in practice.

The following insights regarding AMS for ITS tools typically used in practice were found based on the literature review and interviews with stakeholders:

- There exist a variety of AMS for ITS tools used in practice for different purposes with varying levels of fidelity and resolution. Most of these tools align well with the TAT categories and most are used for operational, planning, design, and evaluation purposes.
- Mobility and environmental impact performance measures are the most prevalent outputs from AMS for ITS tools. Safety measures were largely absent from both stakeholder discussions as well as the literature review.
- While the capabilities of many tools can be extended using APIs and SDKs, there is limited use of tools in practice that employ state of the art analytical and AI/ML functionalities due to the lack of maturity/validated trustworthiness and in-practice applications as well as the black-box nature of the most advanced algorithms. Additionally, AI/ML-derived statistical models are not uncommon to represent traffic dynamics and some physical phenomena for control purposes, but these models are almost always trained offline and are not updated with real-time data.
- While there are some uses of MRM tools in practice, their use as well as the adoption of newer, possibly improved AMS for ITS tools by practitioners appears to be hindered by several key factors:
    - Funding and ROI methods to help present a business case in support of funding.
    - Either lack of required data amount and/or types, or lack of ability to process/understand an overabundance of collected data.
    - Guidance with accompanying training and in-practice use cases.
    - Uncertainty in how to apply research to practice.
- Only a few AMS for ITS tools typically used in practice have real-time/rolling horizon predictive capabilities as most are used for offline planning purposes. However, there are several tools that have recently been released or are under development that are anticipated to have these capabilities.
- Proprietary data (e.g., from INRIX, Wejo, Waze, StreetLight, TomTom) are being purchased or obtained through data sharing agreements by more and more agencies to supplement internal agency collected data to help support AMS for ITS activities.

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

Fifteen (15) gaps/challenges were identified and consolidated (see Table 25**)** based on the state of practice for AMS for ITS tools obtained from the representative, but non-exhaustive literature review and set of practitioner 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 practitioners 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 complementary State of Research 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 1**: Tool license/subscription cost.
- **Gap/Challenge 2**: Extensive programming/ coding/ tool software workforce training/ development required for standard and/or advanced tool use.
- **Gap/Challenge 4**: Lack of ROI analysis and/or guidance for how and when AMS for ITS tools allow for improved practitioner capabilities and support for the various costs associated with investing in new tools.
- **Gap/Challenge 5**: Tool outputs and measures of effectiveness (MOE) may require post-processing for usability.
- **Gap/Challenge 6**: Significant input data amount requirements.
- **Gap/Challenge 7**: Significant CPU/GPU and storage requirements needed to run AMS tools.
- **Gap/Challenge 13**: 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 15**: Gap in transferring knowledge to practitioners to promote adoption of new methods and approaches. Practitioners often do not have the means or examples to be able to apply and/or know when to apply the most robust AMS for ITS research tools to consistent real-world scenarios/use cases. Lack of guidance for how to promote and facilitate adoption of research-developed AMS for ITS tools and methods with state agencies and practitioners.

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Appendix A. Summary of AMS for ITS Tools Used Typically in Practice

Table 26. Summary of AMS for ITS Tools Typically Used in Practice

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
Travel Demand Models	CUBE	• Transportation land-use planning and analysis	• City and regional planning activities • Integrable with Dynameq to model and assess impacts of ITS applications such as ramp metering, transit signal priority, variable speed limits, hard shoulder	• Geometric Data • Current Socioeconomic Data • Forecasts of future population, households, and employment throughout a TAZ • Transit Data • Information about future transportation networks	• Average Traffic Volume, VMT, Average Travel Times, Average Speeds, Transit Ridership, Total Trips, etc.	• Virginia statewide and regional demand modeling • California statewide model to forecast short- and long-distance travel • Washington, DC metro area regional travel demand model	• Its ability to visualize, test, and compare multiple scenarios in one application • Its use of flow charts to group processes to ensure completion of tasks • Its inclusion of one interface for land use and transportation system to support seamless communication and data sharing

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
			running, and HOT lanes				• Its ability to handle time of day and peak spreading models • Its ability to be integrated with Dynameq to create a multiresolution model • Additional skills and training may be required to make full use of the tool's functionalities • Access to this tool requires a paid license
Travel Demand Models	TransCAD	• Forecasting travel demand	• City, region, and country-wide travel demand modeling • Integrable with TransModeler to assess impacts of ITS	• 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, Transit Ridership, Total	• Vermont statewide transportation demand model • Modeled and assessed the impacts of time-of-day tolling on	• The tool's use of a single platform that is able to perform multiple functions, including model application, model estimation, database support, GIS-based analysis, and often graphical

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
			applications such as ramp metering, transit signal priority, variable speed limits, hard shoulder running, and HOT lanes	• Information about future transportation networks	Trips, Total Miles, etc.	Indiana roadways • Model to help quantify the expected impact of new capital projects on roadway snow and ice control operations in Minnesota	and analytical postprocessing • Its capability to support all major methodologies of travel demand modeling including sketch planning methods, four-step demand models, activity-based demand models, and other advanced disaggregate modeling techniques • 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

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
							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 • Additional skills and training may be required to make full use of the tool's functionalities • Access to this tool requires a paid license

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
Travel Demand Models	EMME	• Forecasting travel demand, especially for public transit planning	• Transportation networks at the city, regional, and national levels • Capable of modeling components of ITS such as emerging mobility, including CAVs	• Network Data • Transit data • Traffic Flow/Travel Demand Data	• Traffic Volumes, VMT, Average Travel Times, Average Speeds, Transit Ridership, Total Trips Trip Lists, Trip Tables by Mode, Emissions Rates, Route/Line Profiles (to identify congestion on transit lines and sections where alighting and boarding is prominent), etc.	• Analysis of policies and transit investments related to border access highways at a sub-regional level, considering the uncertainty from emerging vehicle technologies in San Diego, CA • Travel demand modeling and analysis for various Northeastern Illinois Transportation Improvement Program projects	• Its support of open data standards and Python code scripting • EMME allows for inclusion/development of models that can be tailored to support local/user-specific applications • Its support of traditional four-step demand model and agent-based demand modeling • Its support of code-free assembling and running of travel demand models through the use of an automation system called Flow • Its inclusion of transit assignment features that support the modeling of mixed-

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
							mode assignment sequences such as driving, TNCs pick-up, scooter use, etc. • It can be integrated with other modeling tools such as Aimsun Next, MOVES, and GIS-based tools • Additional skills and training may be needed to effectively use the tool • Access to EMME requires a paid license
Travel Demand Models	Visum	• Travel demand tool for analyzing investments in transportation infrastruct	• Transportation networks at the city and regional levels • Does not model ITS applications directly, but	• Geometric Data • Traffic Flow/Travel Demand Data • If integrated with microscopic simulation tools, additional data	• Average Travel Times, Average Speeds, Delay, Density, VMT, etc.	• Multiresolution model using Visum and Vissim to study the impacts of deploying Complete	• Its inclusion of a GUI that enables design of network scenarios • Its support of activity-based demand models, which model

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
		ure and sustainable mobility	when integrated with microscopic tools such as Vissim, impacts of ITS applications can be assessed at the macroscopic level	such as Signal Timing Data may be required		Streets in Florida • Model to evaluate and compare three construction scenarios in Salt Lake City, UT • Travel demand model to evaluate transportation needs in coordination with long-term planning in the City of Duvall, WA	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

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
							• Access to this tool requires a paid license
• Analytical/ Deterministic	HCS	• Planning and operational analysis • Modeling innovative/ alternative intersection types • Analyzing ramp terminals and interchanges	• Link and network wide (comprising of urban streets, arterials, and freeways) analysis, including work zones • Modeling parts/components of ITS applications including HOV/HOT lanes, traffic signal timing optimization (when integrated with TRANSYT-7F or other traffic optimization tools), and active traffic	• Geometric Data and Analysis Settings • Traffic Flow/Travel Demand Data • Signal Timing Data	• 95th Percentile Queue (ft), Control Delay (sec), Percent of Free-flow Speed (%), Percent Time Spent Following (%), Density (veh/ln/mi)), Experienced Travel Time (sec/veh), Travel Time (sec and/or min), Space Mean Speed (mph), LOS, v/c Ratio, etc.	• Analysis of basic and weaving freeway segments, multilane highways, and two-lane highways in Virginia • Capacity analysis and traffic signal coordination for urban arterials; Operational analysis of rural two-lane highways and multilane highways; Express lane analysis on limited access facilities; and	• The tool requires fewer inputs and less time for calibration, analysis, and modeling compared to other tools • Its ability to perform multi-time period analysis, which enables modeling of congestion and queues on arterials and freeways that stretch beyond peak periods • The user interface in HCS is not as visually intuitive as those included in other tools

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
			management for arterials and freeway segments			Capacity analysis of weaving segments and ramp merge/diverge areas for interchanges in Florida • Operational and design analysis of freeway segments, weaving areas, ramp and ramp terminals, multilane highways, two-lane highways, intersections, and transit in Washington State • Analysis of freeway segments, weaving areas,	• This tool is unable to model some lane configurations • Access to HCS requires a paid license and the tool may require some initial training to effectively use it

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
						ramp and ramp terminals, multi-lane highways, two-lane highways, and arterials in Texas	
Analytical / Deterministic	Sidra Intersection	• Analyzing signalized, unsignalized, and roundabout intersections • Primary use in the United States has been for analyzing roundabouts	• Single intersections through networks of intersections • ITS applications such as metered roundabouts	• Geometric Data and Analysis Settings • Traffic Flow/Travel Demand Data	• 95th Percentile Vehicle Queues, Degree of Saturation, LOS, Control Delay, Number of Vehicle Stops, v/c Ratio, and Space Mean Speed	• Roundabout analysis in Virginia, Florida, Washington State, Texas, and Colorado	• Its ability to account for the effects of vehicle arrivals based on adjacent traffic control devices • Its use of a lane-based model that can identify backward spread of congestion, midblock lane changes and unequal approach lane use at closely spaced intersections, which is different from many tools that model traffic at

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
							intersections based on lane groups • In the United States, the use of Sidra is almost exclusively limited to roundabout analysis • Access to the tool requires a paid license, and the tool may require some initial training to effectively use it
Traffic Optimization	Synchro	• Policy, planning, and operational analyses for proposed projects and alternatives	• Link and network wide (comprising of arterials) analysis • ITS applications such as adaptive traffic signal control, variable speed limit, and	• Geometric Data and Analysis Settings • Traffic Flow/Travel Demand Data • Signal Timing Data	• 95th Percentile and Maximum Queue Lengths (ft), Control Delay (sec), LOS, Travel Time (min), Space Mean Speed (mph), v/c Ratio, etc.	• Intersection, arterial, and corridor analysis in Virginia • Capacity analysis and traffic signal optimization on urban arterials; and Network and system performance	• Its ability to model corridors of signalized and unsignalized intersections • Its ability to optimize splits, cycle lengths, phase sequences and offsets • Its inclusion of an interactive GUI. • Synchro is not well-suited for the

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
			reversible lanes			evaluation in Florida • Capacity analysis and traffic signal optimization on urban arterials in Wisconsin	analysis of freeways, interchange systems, and ramps [55] and may not accurately model oversaturated traffic conditions • The latest HCM edition was released in 2022, however, it is unclear to what extent the latest version of Synchro incorporates this edition as well as its adoption in practice • Access to this tool requires a paid license
Traffic Optimization	Vistro	• Traffic signal analysis and optimization for	• Analyzing traditional traffic signal operations, Complete-Streets, and	• Geometric Data and Analysis Data • Travel Demand Data	• Intersection LOS, Turning Movement LOS, Intersection and Turning	• Analysis of a large network of intersections for congestion management monitoring and	• Its network and signal optimization capabilities • The tool is capable of modeling

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
		standard and advanced signalizations needs in coordinated and uncoordinated environments • Traffic impact analyses	access-management projects. • Model advanced traffic signal optimization at individual intersection, districts, or across the entire network, and include CAV market penetration rates.	• Driver and Vehicle Characteristics Data • Signal Timing Data • Pedestrian Data	Movement Delays, v/c Ratios, Intersection Throughput, Turning Movement Throughput, Trave Times, etc.	congestion relief corridor planning studies in Santa Clara Valley, CA • Optimization of signal timings for real-world intersection development planning scenario simulation in North Carolina	pedestrian and bicycle phases • Its incorporation of adaptable traffic signal workflows • It implements HCM methodologies for signalized intersections, stop-controlled intersections, and roundabouts • It is compatible with Vissim and Visum • Its inability to model ramp terminals • Access to Vistro requires a paid license • Additional skills/training may be needed to effectively use the tool

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
Macroscopic Simulation	FREEVAL	• Planning-level capacity analyses for undersaturated and oversaturated conditions • Work zone impact assessments for planning-level and operational-level analyses • Evaluation of managed lanes such as HOV, HOT, and expressways	• Modeling parts/components of ITS applications for traffic incident management, weather traffic management, and work zone traffic maintenance • ITS technologies that can be included are end-of queue advanced warning systems, variable message signs, portable message signs, automatic collision	• Geometric Data and Analysis Settings • Traffic Flow/Travel Demand Data	• 95th, 80th, and 50th Percentile Travel Time Indices, Density (pc/mi/ln), Demand to Capacity Ratio, Space Mean Speed (mph), Vehicle Miles Traveled (veh-miles/interval), Passenger Miles Traveled (p-miles/interval), Vehicle Hours (travel/interval [hrs]), Vehicle Hours Delay (delay/interval [hrs]), and User Cost ($)	• Virginia Freeway Segment Analysis • Pennsylvania Freeway Work Zone Analysis • North Carolina Freeway Work Zone and Reliability • Texas Freeway, Multi-lane Highway, Two-lane Highway, and Managed Lanes Analysis as well as Travel Time and Reliability Analysis	• Its ability to model both undersaturated and oversaturated conditions • This is a free open-source tool maintained by the TRB Committee on Highway and Quality of Service • The tool does not incorporate a graphical interface that can visualize segment coding, which has been shown to make analysts prone to making mistakes when entering network geometries, particularly for large networks • Users have identified the existence of inconsistencies

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
			warning systems, etc.				between demand variability over time and facility travel time that may arise if facility length exceeds 9 -12 miles • Additional skills and training may be required to make full use of the tool's functionalities • Since it is an open-source tool, there is limited technical support available to users
Mesoscopic Simulation	DYNASMART	• Network operational planning tool	• Links and networks • Urban areas of various sizes as well as work zones and evacuation zones	• Geometric Data • Traffic Control Data • Traffic Flow/Travel Demand Data • Vehicles Class • User Classes	• Total Travel Time, Average Travel Time, Vehicle Throughput, Travel Time Index, Buffer Index, Planning Time Index, Misery Index, Total Stopped	• Integrated and operationalized weather-sensitive models to support weather-responsive traffic signal timing implementation	• Its ability to model individual drivers' response to information based on a set of paths rather than the single shortest path • Its ability to expand capabilities and functionality through multiple means

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
			• ITS applications such as ramp metering, variable message signs, in-vehicle traveler information, incident management, HOT lanes, etc.		Time Savings, Percentage of Vehicles Stopped, Stopped Time, etc.	and evaluation in the Riverdale corridor in Ogden, UT • Application of Maryland's Coordinated Highways Action Response Team network along the I-95 corridor between Washington, DC and Baltimore, MD	(e.g., Application Programming Interface (API)) • Its ability to model scenarios with only a fraction of the vehicles equipped to receive travel information • The tool is open-source and does not require a paid license to access • Since it is an open-source tool, there is limited technical support available to users • DYNAMSMART requires significant efforts/resources to extend tool's capability through the API • This tool does not model

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
							bicycle/pedestrian paths, transit roadways and facilities, or parking management • Additional training and skills may be needed to effectively use the tool
Mesoscopic Simulation	DynusT	• Modeling and assessing system-wide traffic flow dynamics based on traveler response to information and prevailing traffic/travel conditions	• Links and networks • DTA on regional-level networks over a long simulation period • ITS technologies such as dynamic message signs, ramp meters, in-vehicle guidance	• Geometric Data • Traffic Control Data • Traffic Flow/Travel Demand Data • Vehicle Classes • User Classes	• Travel Time, Travel Speed, VMT, Delay, etc. • These can be estimated for each user class at the link/lane level, path-level, or network level	• Modeling of the following ICM strategies: ramp metering, congestion pricing, and transit simulation and assignment, for various incident scenarios for Minneapolis, MN • Modeling of various work zone traffic management	• Its anisotropic mesoscopic simulation property that increases the simulation speed and allows for computational efficiency • Its ability to model a wide range of scenarios that include passenger vehicles, trucks, and HOV lane restrictions, and other user road classes

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
			systems, and strategies such as work zone management, incident management, and special event management			scenarios in Detroit, MI • Modeling of the regional road network in Maricopa County, GA to study operational strategies intended to mitigate impacts of work zones, crashes, road closures, etc.	• Its ability to specify time-varying O-D matrices in a wide range of time resolutions from minutes to hours • Its ability to be integrated with ABMs • The tool requiring significant efforts/resources to extend the tool's capabilities through its API • Its inability to explicitly define individual lanes, therefore not allowing lane-level phenomena to be replicated. Also, it is not able to model ring barrier controllers or pedestrian/bicycle paths

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
							• Access to DynusT requires a paid license and the tool may require additional skills and/or training to effectively use it
Mesoscopic Simulation	Dynameq	• Analyze existing transportation network issues and plan for improvements/strategies	• Single congested corridor to an entire city • ITS strategies and applications including ramp metering, transit signal priority, variable speed limits, hard shoulder running, and HOT lanes • Transit-focused strategies such as bus	• Geometric Data • Traffic Control Data • Traffic Flow/Travel Demand Data • Vehicle Classes • Vehicle Characteristics	• Travel Time, Travel Speed, VMT, Delay, Queues, etc. • These can be estimated for each road user/vehicle class at the lane level, path-level, or network level	• DTA model for the entire city of San Francisco, CA to enable effective evaluation of projects within the region • Citywide traffic simulation and DTA model to assess multiple operational planning studies in support of the Transportation Master Plan for city of Edmonton,	• Its ability to simulate vehicles at the lane level • Its ability to model multiple scenarios with a variety of modes that include passenger vehicles, trucks, and HOV lane restrictions • Its ability to model restricted movements such as lane restrictions for vehicle types and vehicle occupancy requirements

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
			rapid transit and light rail transit			Alberta, and its holistic view of transport as an interconnected, multimodal system • Corridor model to evaluate potential improvement strategies along I-70 in Kansas City, MO	• Its ability to model roundabouts and rotaries • Its capabilities can be extended using the tool's Python-based API • Its inability to model pedestrian/bicycles paths and requiring additional resources to extend the tool's capability through its API • Access to Dynameq requires a paid license, and the tool may require additional training and skills to effectively use it
Microscopic Simulation	Vissim	• Policy, planning, and operational purposes	• Link and network wide (comprising of arterials and	• Geometric Data and Analysis Data • Travel Demand Data	• Density (veh/ln/mi), Maximum Queue Length (ft), Microsimulatio	• Arterial and freeway operation studies, toll plaza and gated	• Its ability to simulate different road user classes such as buses, trucks,

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
			freeways) analysis • ITS applications including ramp metering, adaptive signal control, LRT and bus signal priority, traffic signal preemption at (or near) railroad crossing, emergency vehicle preemption, dynamic speed control, dynamic lane assignment signals, and changeable message signs	• Driver and Vehicle Characteristics • Signal Timing Data • Pedestrian Data	n Delay (sec/veh), Space Mean Speed (mph), Time Mean Speed (mph), Travel Time (sec), 95th Percentile Queue Length (ft), O-D Pair Results, Pedestrian Analysis Results (Maximum/Minimum Number of Pedestrians, Density, Speed, Travel Time, Delay, etc.), Emissions, Fuel Consumption	analyses, managed lane or ramp metering analyses in Virginia • Freeway operation studies, transit modeling in Washington, DC • Operational analysis for limited access facilities; Capacity analysis of weaving/merging/diverging segments, freeways, and ramps for interchanges; and Capacity analysis and traffic signal optimization for	pedestrians, and bicyclists • Its incorporation of CAV features, including communications and cooperation among vehicles • Vissim is a high-fidelity multiresolution 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

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
						urban arterials in Florida • Operations analysis for freeways and ramps, arterials, transit, and CVs/AVs in Michigan • Capacity analysis of weaving/merging/diverging segments, freeways, and ramps for interchanges; and Capacity analysis and traffic signal optimization for urban arterials in Wisconsin • Operations analysis for freeways and	and macroscopic simulation tools

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
						ramps, arterials, transit, and CVs/AVs in Virginia	
Microscopic Simulation	SimTraffic	• Used at the project planning stage to select preferred alternatives and at the project implementation stage to determine roadway and signal impacts • Arterial traffic signal control coordination and optimizatio	• Link and network (intersections, arterials, and corridors) analysis • ITS applications such as adaptive traffic signal control	• Geometric Data • Travel Demand Data • Driver and Vehicle Characteristics • Pedestrian Data • Signal Timing Data	• 95th Percentile and Maximum Queue Lengths (ft), Delay (sec), Travel Time (min), Space Mean Speed (mph), v/c Ratio, etc.	• Intersections, arterials, and corridors analysis in Virginia • Capacity analysis and traffic signal optimization for urban arterials; and Network and system performance evaluation in Florida • Capacity analysis and traffic signal optimization for urban arterials in Wisconsin	• Its ability to effectively model traffic flow, traffic signal progression, and optimization of traffic signal timing • Its ability to analyze intersection operations under heavy congestion • Its ability to model networks with signalized and unsignalized intersections • SimTraffic does not have the functionality to analyze freeway or interchange systems, or model

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
		n, intersection capacity analysis, and network and system performance evaluation					detailed transit operations • SimTraffic does not have as high fidelity as most other microscopic simulation tools • Access to SimTraffic requires a paid license, and the tool may require additional training or skills to effectively use it
Microscopic Simulation	Aimsun	• Policy and planning modeling, multimodal transportation analysis, real-time transportation management,	• Modeling at multiple scale levels including the link and network level (comprising of arterials and freeways), urban area level, and regional levels	• 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),	• Urban network congestion management using real-time data for signal control in Midtown Manhattan, New York City, NY • Real-time modeling for a decision	• 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

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
		demand modeling, estimating the impact of emerging mobility technologies, energy and emissions modeling, and cost-benefit analysis of ITS technologies/strategies	• ITS applications such as ramp metering, adaptive signal control, LRT and bus signal priority, traffic signal preemption at (or near) railroad crossing, emergency vehicle preemption, dynamic speed control, dynamic lane assignment signals, and changeable message signs		Mean Queue Length (number of vehicles), Maximum Queue Length, Total Number of Stops, Fuel Consumption (liters), Pollutant Emission (kilograms), etc.	support system as part of the ICMS along I-15 corridor in San Diego, CA, including the freeway corridors, parallel arterials, and transit operations • Real-time modeling for a decision support system as part of ICMS along I-4 corridor in Florida, including the freeway corridors, parallel arterials, and transit operations	• 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 • Access to Aimsun requires a paid license and the tool may require additional training or skills to effectively use it

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
						• Analysis of small area networks to evaluate impacts of traveler information and compare alternatives in Virginia	
Microscopic Simulation	Paramics	• Modeling and simulating individual components of the traffic stream for planning and analysis purpose	• Links, networks, urban areas, and entire cities • Public transportation simulation and it has a built-in 3D simulation visualization tool for generating videos • ITS strategies and components	• Geometric Data • Traffic Control Data • Traffic Flow/Travel Demand Data • Driver and Vehicle Characteristics • Pedestrian Data	• VMT, VHT, Average Delay (seconds), Density (vehicles/km), Vehicle Throughput (vehicles/hour), Average Speed (km/hour), Average Stops, Average Travel Time (seconds or minutes), Total Time Stopped for Public Transit (seconds or	• Simulation-based corridor decision making tool that can help evaluate alternative corridor scenarios based on corridor level mobility, fuel consumption, and emissions in New York • Model to assess the performance of	• Its ability to perform large-scale microsimulations • Its ability to perform economic assessments of improvement projects to aid in decision making • Its ability to incorporate pedestrians and bicyclists in modeling and visualization

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
			such as ramp metering, reversible lanes, dynamic lane management, hard shoulder running, active traffic management strategies, eco-speed harmonization, connected and automated vehicles, etc. • Economic assessments and emissions modeling		minutes), Passengers Alighting, etc.	two roundabouts in Mississippi	• It has built-in 3D visualization • Paramics has potentially time- and data-intense model development and calibration, depending on the size of network and complexity of scenario • It does not have the capability to output signal coordination timing • Outputs and MOEs from Paramics may require post-processing • Access to the tool requires a paid license and the tool may require additional training or skills to effectively use it

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
Microscopic Simulation	CORSIM	• Traffic operations analysis • Modeling interactions between freeways and urban streets, and perform route assignments using DTA • Analyzing active traffic management strategies for arterials and freeways • Assessing and	• Modeling links and networks • ITS applications including ramp metering, adaptive signal control, transit signal priority, traffic signal preemption at (or near) railroad crossing, emergency vehicle preemption, incident detection, managed lanes such as HOV and HOT lanes, etc.	• 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 (seconds/vehicle), Fuel Consumption (gallons), Pollutant Emission (kilograms/ mile-hour), etc.	• Traffic signal optimization for an urban roadway network in Chicago, IL • Model to assist with the assessment of preliminary engineering, roadway design, traffic system performance, and weaving area and ramp terminal analysis in Florida • Analysis of small area networks to evaluate impacts of traveler information and compare	• Its ability to accommodate time-varying demand and 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 • Access to CORSIM requires a paid license and the tool

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
		testing signal timing optimization in conjunction with TRANSYT-7F, HCS tools, and other algorithms				alternatives in Virginia	may require additional training or skills to effectively use it
Microscopic Simulation	TransModeler	• Planning for traffic operations • Comparing impacts of operational strategies and design alternatives on a wide variety of	• Modeling and simulating links, networks, urban areas, counties, and regions • ITS strategies and technologies including reversible lanes, hard shoulder running, speed	• Geometric Data • Signal Timing 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), Average Stops, Average Travel Time (seconds or minutes), Bus Delay Per Vehicle	• A 450-square-mile microscopic traffic simulation model spanning most of Lake County, CA used to evaluate traffic demand within the study area • Modeling and simulation of engineering design	• It has multiresolution hybrid simulation capabilities in which high-fidelity microscopic simulation can be readily intermixed with mesoscopic simulation • TransModeler is a GIS-based tool, which makes it simple to automatically load map layers and

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
		road networks • Evaluating the impacts of future planning scenarios through integration with TransCAD, a travel demand forecasting software	harmonization, adaptive ramp metering, variable speed limits, electronic toll collection, managed lanes, signal preemption, transit signal priority, actuated signal control, CAVs, etc. • Modeling and simulating on-street parking		(seconds/vehicle), etc.	alternatives and ITS applications to reduce congestion and improve roadway safety on freeway and arterial/local street facilities in North Carolina • Model to demonstrate feasibility of deploying ICM along the I-270 corridor in Montgomery County, MD • Model for testing alternative build scenarios under future conditions for the State Route 91	aerial imagery from Google Earth, Google Maps, OpenStreetMap, and 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 the tool to report simulation-based LOS metrics • Its ability to integrate with the travel demand forecasting tool TransCAD • The tool has built-in 3D visualization

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
						Corridor System Management Plan in Orange County, CA	through Unity 3D Viewer • Outputs and MOEs from TransModeler usually require post-processing and 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

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
							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	TRANSIMS	• Travel forecasting and microscopic simulation models developed for regional	• Modeling and simulation of large road and transit networks (i.e., over 100,000 links) that can accommodate over 30 million travelers	• Geometric Data • Signal Timing Data • Traffic Flow/Travel Demand Data	• Measures at the macroscopic level include VMT, VHT, Total Travel Time, Average Travel Time, and Pollutant Levels	• Model to assess proposed land use changes and their impacts on travel, providing insights on operational	• The tool is open-source and does not require a paid license to access • Its ability to support large-scale microscopic simulations, enabling the evaluation of

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
		transportation planning • Modeling evacuations, traveler response to tolls, analysis of safety benefits of alternatives, etc.	• ITS applications including dynamic HOT lanes, evacuation, and traffic management under inclement weather conditions	• Driver and Vehicle Characteristics • Other Data (e.g., census)	• Measures at the microscopic level include Average Travel Time, Average Speed, Vehicle Throughput, and Intersection Measures (e.g., Total Delay, Delays Per Cycle, Number of Stopped Vehicles in Queue, etc.)	impacts compared with traditional travel demand models in California	strategy impacts at the tactical/local level through the system-wide level for large road and transit networks, accommodating large populations • TRANSIMS requires significant Central Processing Unit (CPU) time and extensive storage capacity • Since it is an open-source tool, there is limited technical support available to users
Microscopic Simulation	SUMO	• Assessing operational strategies as part of planning • Simulating vehicular communic	• Modeling and simulation of links and large networks • ITS applications and technologies	• Geometric Data • Traffic Control Data • Traffic Flow/Travel Demand Data	• Vehicle Throughput (vehicles/hour), Average Speed (km/hour), Average Stops, Average Travel Time (seconds	• A model to detect and quickly respond to highway incidents to mitigate traffic flow	• The tool is open-source and does not require a paid license to access • Its ability to model large-scale

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
		ations (i.e., V2X communications)	including adaptive signal control, variable speed limits, speed harmonization, hard shoulder running, CAVs, etc.	• Driver and Vehicle Characteristics • Pedestrian Data	or minutes), Density (vehicles/km), Occupancy (%), Average Delay (seconds), etc.	breakdown in Wichita, KS	microscopic simulations • Its ability to model and simulate multiple ITS applications • Its compatibility with external software such as Vissim, Visum, MATSim, and others • Usage of SUMO requires prior knowledge of Python, C++, or the command line programming as well as the ability to process XML files for initial setup and implementation • Since it is 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
Other	MOVES	• Estimating exhaust and evaporative emissions as well as brake and tire wear emissions from all types of vehicles on a roadway	• Estimation of emissions at the corridor/intersection level, traffic analysis zone level, or the national level • For ITS roadway environmental monitoring applications implemented at the corridor/intersection level, MOVES can use simulated vehicle trajectories to estimate emissions	• VMT by vehicle type, the number of each type of vehicle, vehicle age distributions, fuel information (i.e., fuel supply, fuel formulation, fuel usage fraction, etc.), meteorological data, road type distribution, retrofit data, average speed distribution, etc.	• N_2O, Primary Exhaust PM2.5-Total, Primary Exhaust PM10-Total, Primary PM2.5 – Brake Wear Particulate, SO_2, Total Energy Consumption, etc.	• Texas Transportation Institute estimated emissions from trucks at the Port of Houston using the MOVES tool to support transportation and air quality planning • Modeling of automated vehicle behavior in microsimulation tools and feeding simulated vehicle trajectories into MOVES for emissions estimation	• The tool is open-source and does not require a paid license to access • Its ability to estimate emissions at different scales depending on use case • It requires detailed knowledge of Excel and the Visual Basic programming tool • Feeding simulated vehicle trajectories as input to MOVES requires conversion from simulation file format to the MOVES file format. This conversion process may require additional skills/training to complete • Since it is an open-source tool, there is

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
							limited technical support available to users
Other	SSAM	• Automatic identification, classification, and evaluation of traffic conflicts in the vehicle trajectory data output from microscopic traffic simulation models	• Traffic conflicts on all types of road facilities • For ITS applications implemented in microscopic simulation tools, SSAM is able to identify and evaluate traffic conflicts based on simulated vehicle trajectories	• Vehicle Trajectory Data and threshold values for TTC and PET	• Threshold values from two performance measures, TTC and PET, are used as inputs to identify traffic conflicts • Outputs include conflict counts and conflict events, which can also be categorized based on the type of driving maneuver (crossing, rear-end, and lane-change events)	• Investigation of the effectiveness of using the SSAM to evaluate highway or intersection safety, particularly the safety effects of multiple access management alternatives in Utah	• The tool is open-source and does not require a paid license to access • It addresses limitations in basing safety analysis on police-reported crash reports, which is often too slow to reveal the need for remediation • SSAM is supported by multiple commonly used microscopic simulation tools • SSAM requires a rigorous calibration procedure be applied to the microscopic simulation model whose output

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
							vehicle trajectories will be inputs to the tool in order to generate reliable conflict results • There is a possibility that the tool produces unreliable conflict results since simulation models may not accurately represent actual driving behavior and often fail to capture the actual mechanisms generating near-misses • SSAM may require additional training and skills to effectively use the tool • Since it is an open-source tool, there is limited technical

Principal Tool Category	Tool Name	Primary Purpose/ Objective	Scope	Data Inputs/ Requirements	Performance Measures/ Outputs	Use Cases	Key Findings
							support available to users

Appendix B. Stakeholder Discussion Topics

Below are the two sets of interview questions asked during the interviews stakeholders to solicit inputs primarily on the state of practice and possibly on the state of research for AMS for ITS tools and identify gaps and challenges. The first set of interview questions was asked to practitioners and the second set of interview questions was asked to tool developers. Practitioners in this context 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 two sets of questions, but differences exist that are specific to the stakeholder groups.

Practitioner Interview Questions

Short Answer Questions:

1) What specific traffic AMS tool(s) does your agency use in practice, including any of the following?
   a) Impact of emerging mobility and technologies (including ITS) analysis/modeling
   b) Microscopic/mesoscopic/macroscopic modeling and/or simulation
   c) Multiresolution modeling (MRM)
   d) Transportation network and system optimization
   e) Multimodal transportation planning
   f) Activity- and/or agent-based modeling
   g) Static and/or dynamic analysis/modeling
   h) Micro-mobility analysis and modeling
   i) Energy and emissions analysis/modeling
   j) Traffic safety analysis/modeling
2) What functions does your agency use/has your agency used AMS tools to perform currently/within the past 5 years, including the following?
   a) Evaluating impacts of emerging technologies and new data sources on transportation systems.
   b) Simulating, evaluating, and/or optimizing transportation facility and system operations.
   c) Modeling existing operations and predicting likely outcomes for proposed alternative designs.

  d) Evaluating various analytical contexts such as planning, design, and operations/maintenance.
  e) Any other key use cases of AMS tools by your agency.

3) What specific performance measures are considered in your agency's AMS activities? Are these measures directly reported from AMS tool(s) (name of the tool) and/or are these measures indirectly generated/computed (e.g., measures requiring additional processing of AMS tool output data)?

4) What type of data do you use for model calibration and validation? What are some of the parameters your agency incorporates for model calibration and validation?

5) How do you collect the input data for AMS tools? Is there any open-source data that your agency utilizes for AMS? Are there any data sources or data types that are currently not being used that could be useful?

6) Does your agency have a framework/process for assessing the technology readiness level and/or capability maturity of AMS tools?
  a) If yes, please elaborate on this.
  b) If no, please explain how AMS tools are selected for various activities/functions.

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.)?

4) When you are interested in learning more about AMS tools or are seeking technical support, what resources/entities do you turn to first?

5) Is there adequate guidance in the resources you currently use to help you utilize AMS tools effectively? What kind of additional support or training do you anticipate needing to make the most effective use of a new traffic analysis tool?

6) Are there any materials (i.e., reports, presentations, fact sheets, etc.), either publicly available or in-house, that you think we should review as part of this effort, and you can share with us?

Tool Developer Interview Questions

Short Answer Questions

1) What AMS tools does your organization develop? Are they able to perform any of the following?
    a) Impact of emerging mobility and technologies (including ITS) analysis/modeling
    b) Microscopic/mesoscopic/macroscopic modeling and/or simulation
    c) Multiresolution modeling (MRM)
    d) Transportation network and system optimization
    e) Multimodal transportation planning
    f) Activity- and/or agent-based modeling
    g) Static and/or dynamic analysis/modeling
    h) Micro-mobility analysis and modeling
    i) Energy and emissions analysis/modeling
    j) Traffic safety analysis/modeling
    k) Others
2) What are the key use cases of your AMS tool(s)? Are these use cases for practice and/or research?
3) What are the typical performance measures your AMS tool(s) generate? Are these measures directly reported from the AMS tool(s) and/or obtained through further processing of raw output data?
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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