Multiresolution Modeling for Traffic Analysis: State-of-Practice and Gap Analysis Report

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FOREWORD

Multiresolution modeling (MRM) is capable of producing great insights into the complex mobility challenges associated with surface transportation. This report provides a unique compendium of MRM information from some of the world's foremost experts in MRM, plus additional feedback from agencies who have had difficulties in adopting MRM. This state-of-practice and gap analysis report is a precursor to the final MRM report, which will propose a recommended MRM methodology and report the outcomes of three MRM case studies. Ultimately, both reports will be of interest to State and local departments of transportation who are interested in advancing their traffic analysis capabilities.

Brian P. Cronin, P.E.
Director, Office of Safety and Operations
Research and Development

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16. Abstract

The Federal Highway Administration and Traffic Analysis and Simulation Pooled Fund Study sponsored a research project on multiresolution modeling (MRM). The project's goal was to develop consistent definitions and a unified modeling framework for transportation professionals to help them better understand the opportunities and challenges associated with MRM. This state-of-practice and gap analysis report provides a review of MRM terminology, tools, and literature. It further reports the outcomes from a series of teleconferences with 19 agencies and companies with a vested interest in MRM. These discussions found increased interest in MRM as a means to make simulation results more defendable. However, the study found that there are still issues facing agencies that utilize or desire to utilize MRM as part of their modeling practices. These findings will provide an important point for future advancement in the research, development, and application of MRM in transportation engineering.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or “metric ton”)	Mg (or “t”)
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or “t”)	megagrams (or “metric ton”)	1.103	short tons (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ABBREVIATIONS

ABM	activity-based models
ABMS	agent-based modeling and simulation
AMS	analysis, modeling, and simulation
ARC	Atlanta Regional Commission
ARDOT	Arkansas Department of Transportation
ATDM	active transportation and demand management
BEAM	Behavior, Energy, Autonomy, and Mobility
BRT	bus rapid transit
CAV	connected and automated vehicle
CG	computational graph
CMM	capability maturity model
CTM	cell transmission model
CV	connected vehicle
DFF	data fusion-based framework
DMA	dynamic mobility applications
DOE	U.S. Department of Energy
DOT	department of transportation
DTA	dynamic traffic assignment
DUE	dynamic user equilibrium
FAST-TrIPs	Flexible Assignment and Simulation Tool for Transit and Intermodal Passengers
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
FTF	flow transition-based framework
GIS	geographic information system
GMNS	General Modeling Network Specification
HCM	Highway Capacity Manual
HOT	high-occupancy toll
HOV	high-occupancy vehicle
ICM	Integrated Corridor Management
ITS	intelligent transportation system
LOS	level of service
MaaS	mobility as a service
MBC	model-based consistency
MDOT SHA	Maryland Department of Transportation State Highway Administration
MEP	mobility energy productivity
MoEs	measures of effectiveness
MOVES	Motor Vehicle Emission Simulator
MPO	metropolitan planning organization
MRM	multiresolution modeling
NCHRP	National Cooperative Highway Research Program
NDOT	Nevada Department of Transportation
NeXTA	Network Explorer for Traffic Analysis
O-D	origin-destination
ODME	origin destination matrix estimation

OMX	open matrix
PBC	process-based consistency
POLARIS	Planning and Operations Language for Agent-based Regional Integrated Simulation
PSO	particle swarm optimization
PSRC	Puget Sound Regional Council
SHRP 2	Second Strategic Highway Research Program
SMART	Systems and Modeling for Accelerated Research in Transportation
STA	static traffic assignment
TAZ	traffic analysis zone
TDM	travel demand management
TIM	traffic incident management
TMC	traffic management center
TRL	technology readiness level
TSMO	transportation system management and operations
UE	user equilibrium
USDOT	U.S. Department of Transportation
VDOT	Virginia Department of Transportation
VMT	vehicle miles traveled
VOR	value of reliability
VOT	value of time
WisDOT	Wisconsin Department of Transportation

CHAPTER 1. INTRODUCTION

Multiresolution modeling (MRM) has been widely studied by both researchers and practitioners. MRM is an integrated modeling framework where analysts jointly use macroscopic, mesoscopic, and microscopic transportation analysis tools to solve a set of transportation questions under different scenarios.

The goal of this report is to systematically review the state-of-the-art and state-of-the-practice of existing MRM approaches, the potential developments of MRM, and the use of MRM. The MRM frameworks vary widely in their theories and applications, and different models have different simulation granularity, representation (vehicle, cell, and flow), and data requirements. This report attempts to summarize the critical characteristics of the MRM studies, the issues reported in these studies, and the applications and attitudes of State agencies in relation to MRM.

Isolated models at different levels of resolution have their advantages and disadvantages, and none can completely replace another. With this recognition, this report also focuses on reviewing the existing knowledge and applications about how to establish the relationship between the classically isolated simulation tools (i.e., macroscopic, mesoscopic, and microscopic simulations) and the integrated MRM systems.

The objectives of this report are to:

- Explain the terminologies and concepts of MRM and various MRM methodologies in the existing literature.
- Summarize the relationship between MRM and different fidelity of simulation models.
- Review related tools that emerged in existing transportation studies and applications.
- Summarize the findings from the teleconferences conducted with the users and vendors of MRM tools.
- Review MRM applications that have emerged in transportation studies in the past few years and the related experiences and lessons learned.
- Assess hurdles to widespread adoption of MRM at public agencies.

This report is organized into the following chapters:

- Chapter 2 introduces the fundamental terminologies and definitions of MRM and presents both benefits and challenges of each method.
- Chapter 3 reviews the existing tools related to MRM applications.
- Chapter 4 summarizes the findings from the teleconferences with MRM experts.
- Chapter 5 presents an extensive review of literature on the subject.

- Chapter 6 provides a qualitative analysis of text-based data assembled from the literature reviews and the MRM expert teleconferences.
- Chapter 7 summarizes outcomes from the teleconferences with agencies struggling to adopt MRM.
- Chapter 8 provides an analysis of gaps and barriers to adoption of MRM by transportation agencies.
- Chapter 9 provides conclusions and recommendations from the overall report.

CHAPTER 2. TERMINOLOGY AND DEFINITIONS

MRM is a framework for integrating different levels of simulations and facilitating consistent modeling efforts across different representations. This chapter lists some essential concepts in the MRM theories and answers the following two questions: What are the related basic concepts in existing isolated traffic simulation models? What are the basic features of MRM?

TRANSPORTATION SYSTEMS MODELS

This section provides basic definitions associated with the components of MRM. The section defines resolutions and fidelity, macroscopic models, mesoscopic models, microscopic models, agent-based models, skim matrices, demand forecasting, and traffic flow models.

Resolutions and Fidelity

Resolution is the degree of detail and precision used in the representation of real-world aspects in a model or simulation (Army Modeling and Simulation Office 2020). Fine-grained spatial resolutions make corridors, roads, and lane representation possible. A detailed temporal resolution uses a simulation clock with timestamps in seconds. Transportation simulation considers three classes of modeling approaches, defined by their spatial and temporal resolutions: macroscopic, mesoscopic, and microscopic (Rabelo et al. 2015; Sloboden et al. 2012).

There is a subtle difference between model resolution and fidelity. In general, resolution is about the level of detail in which the model represents the underlying network, supply, or demand elements in a broader sense. Fidelity is more concerned about the accuracy of representation, that is, the degree to which a model or simulation reproduces the state and behavior of a real-world object (or the perception of a real-world object, feature, condition, or chosen standard) in a measurable or perceivable manner. Fidelity is generally applicable to the measures, standards, or perceptions used in assessing or stating it (North Atlantic Treaty n.d.).

Different types of analyses should systematically determine the level of detail required for a model. A rule of thumb is to model the transportation facilities that are one functional class level below the level of interest for the study. Some dynamic traffic assignment (DTA) tools use low-fidelity microscopic models to approximate the mesoscopic traffic behavior. In this case, low-fidelity microscopic simulation tools only use simple car-following and allow limited lane changing within a link.

Macroscopic Models

Analysts have traditionally used macroscopic models most frequently, due to wider availability and lower computation times compared to mesoscopic and microscopic models. Macroscopic models reflect the static or semidynamic routing behavior, using instantaneous travel times, and the deterministic relationships between the demand and speed of the traffic stream.

The input data and process steps for the macroscopic models are:

- Network information: nodes and links files in lower fidelity.
- Transportation facility characteristics in different areas (e.g., speed limits, calibrated capacities, and free-flow speed).
- Existing travel patterns (typically expressed by origin-destination [O-D] matrices in different peak periods).
- Traffic measurements (e.g., link counts or speed files).
- Land-use and social-economic factors, with their historical data and trend analyses (e.g., population growth, household income and vehicle ownership, the state of employment in a region).

Outputs from macroscopic models include path and link volumes, as well as the travel time of the paths for each O-D pair. Macroscopic models apply link capacity functions (or volume-delay functions) to describe the volume-speed relationship in macroscopic simulation models with a volume-capacity (V/C) ratio (e.g., Bureau of Public Roads formed function) (Banister 1995). One should note that there are different types of capacity values in the V/C ratio. Branston defined theoretical capacity as the maximum number of vehicles that can pass a given point on a roadway or in a designated lane during a specified period without the oversaturated density to cause unreasonable delay under prevailing traffic and control conditions (Branston, 1976). Highway Capacity Manual (HCM) methods calculate a range of "service-flow rates" corresponding to different operational conditions of a traffic stream, or levels of service (LOS), rather than one "practical capacity" (Transportation Research Board 2016). Current practices commonly use "ultimate capacity" (i.e., LOS E) to develop parameters in volume-to-capacity functions. To better represent the traffic congestion when there is a queue within the segment, engineers could measure the actual queue discharge rates through the bottlenecks and examine the relationship between the prebreakdown maximum flow rates and the average discharge rates after the traffic breakdown.

Widely used link capacity functions share similar characteristics as follows. They treat each roadway segment as independent without considering queue spillback, and modeled traffic volume/demand can and often does exceed the capacity, which misrepresents traffic flows on the over-capacity segment (Branston 1976).

The advantage of macroscopic models is that they are less complicated and have considerably lower computer requirements than microscopic models. Examples are those implemented in the freeway facility procedure of the HCM (Transportation Research Board 2016). Macroscopic simulation tools are generally best suited for four types of analyses: analyses with relatively large spatial and temporal resolutions, initial assessment of improvement alternatives, analyses that do not require a high level of accuracy, and in conditions with relatively low congestion levels. Macroscopic models have fewer demanding computer requirements than microscopic models. In traffic demand forecasting, macroscopic models also refer to regional travel demand models for both traditional trip-based models and activity-based models (ABM) (Sloboden et al. 2012).

From the perspective of MRM, if the analyst obtains inaccurate inputs for microsimulation models (e.g., overestimated traffic demand on capacitated links) from the macroscopic models (which generally have less restrictive discharge rate constraints at bottlenecks), it might lead to flawed outputs.

Mesoscopic Models

Motivated by a wide range of operational planning needs, such as regionwide dynamic traffic analysis and route guidance provision, mesoscopic models have been increasingly recognized as an important tool for assessing the operational performance of those applications. Mesoscopic models normally describe the traffic facilities at a higher level of resolution compared with macroscopic models, but the behavior and interactions of vehicles exhibits a lower level of fidelity compared with microscopic models. Generally, mesoscopic simulation models aim to fill the gaps between the aggregate level approach of macroscopic models and the individual interactions of the microscopic ones.

The input data and process steps for the mesoscopic models are:

- Network information, including network or corridor with individual segment levels of links with geographic lane changes.
- Existing transportation facilities in different areas (e.g., speed limits, calibrated time-dependent capacities, and macroscopic traffic flow parameters).
- Travel demand profile based on time of day.
- Traffic measurements (e.g., link counts or speed files).
- Traffic information and demand management strategies and scenarios.

Outputs from mesoscopic models include time-varying traffic-flow dynamics and traveler path-choice behavior.

Mesoscopic models can generate and track more precise individual vehicles or packets of vehicles than macroscopic models, especially the movement in intersections (Jayakrishnan 1994; Ben-Akiva et al. 2002; Zhou 2014). Although the movements of the vehicles (or packets) still follow the macroscopic representation of traffic flow and reflect the speed on the travel link, mesoscopic models have the advantage of considering queuing and spillback due to the subject-link capacity and downstream-link queuing capacity.

Although mesoscopic models provide less fidelity than microscopic models, they provide better computational and modeling efficiency than microscopic models. As in microscopic models, the mesoscopic models' unit of traffic flow is the individual vehicle. It is notable that mesoscopic models' DTA applications are strongly associated with mesoscopic-type modeling methods (Sloboden et al. 2012). Thus, analysts have mainly used these mesoscopic models in conjunction with DTA that requires iteration between the assignment and the loading (performance estimation) steps (Banister 1995).

Microscopic Models

Analysts use microscopic simulations when a detailed operational analysis is needed (Ben-Akiva et al. 1997; Fellendorf 1996). Microscopic models simulate the movement of individual vehicles and vehicle-to-vehicle interactions based on car-following, gap acceptance, and lane-changing theories (Banister 1995). The simulations track vehicles through the network over small time intervals, generally at a fraction-of-a-second resolution (e.g., every tenth of a second). Typically, vehicles enter a transportation network using a statistical distribution of arrivals (a stochastic process). The simulation tracks vehicles through the network over small time intervals (e.g., 1 s or a fraction of a second). Typically, the simulation assigns a destination, a vehicle type, and a driver type to each vehicle upon entry.

The input data and process steps for the mesoscopic models are:

- High-fidelity network with lane-changing lanes and details in intersections.
- Input demands as (time dependent) O-D matrices, path-choice behaviors of travelers on segment levels of links, and turning movement counts.
- Traffic information and demand management strategies and scenarios.

The outputs are the trajectories of individual vehicles.

It is notable that more computer time and storage are required for microscopic models than macroscopic and mesoscopic models, thereby usually limiting the network size and the number of simulation runs that can be completed (Sbayti 2010). Microscopic models, on the other hand, can represent vehicles more realistically than models at lower levels of resolution. Microscopic models theoretically are more responsive to different traffic-control strategies, can produce more accurate measures of effectiveness (MoEs), and provide enough flexibility to test various combinations of supply and demand for roadway management strategies.

Agent-Based Modeling and Simulation

Agent-based modeling and simulation (ABMS) is a modeling approach for simulating the actions and interactions of autonomous individuals, assessing their effects on the system as a whole. The basic idea of ABMS is that complex phenomena are simply systems of autonomous agents following rules of interaction. In contrast to the traditional event simulation, which assumes that entities follow a sequence of processes, ABMS defines the local behavior rules of the underlying entities to reveal the emerging behaviors of the whole system. ABMS is widely used in modeling human social and organizational behavior and individual decisionmaking (Zheng et al. 2013).

Skim Matrices

A “skim” refers to a matrix of the values of the impedance between zones in traffic demand forecasting models. Modelers usually estimate the impedance values based on the traffic-flow model results. These impedances can be a combination of travel times, distances, costs, and/or any other parameter that can help to assess the disutility of travel between the zones. They are also potentially helpful in estimating the zone-to-zone travel demands in demand-forecasting models.

DEMAND FORECASTING MODELS AND TRAFFIC FLOW MODELS

Demand models have existed for decades as part of the urban transportation planning modeling process (Patriksson 2015). Practitioners generally categorize transportation planning tools as macroscopic, mesoscopic, and microscopic models, based on the resolution or fidelity at which vehicle flows are simulated.

There are also traffic flow models describing stream characteristics on freeways with different levels of resolutions. In traffic flow theories, macroscopic models represent the characteristics of the traffic flow using analytical models such as the fundamental diagram (Newell 1993; May 1990). The multiregime models have also proposed to combine both the free-flow region and the congested-flow region. Microscopic traffic models define the operation of a traffic system based on individual vehicle characteristics. Microscopic traffic models are calibrated using disaggregated data. Researchers regard microscopic traffic models as noncontinuum models, which involve input parameters such as lane changing, free flowing, car following, and route choices in calibrating. For example, private sector auto manufacturers derived relationships between the responses of drivers involved in the car-following behavior.

BASE YEAR DATA INVENTORY

After agencies obtain agreement on the demand forecasting modeling objectives, the relevant data can be prepared to include the following four categories: network and transport facilities, travel demand profiles, social-economic data, and land-use models.

Network and Transportation Facilities

According to demand and activity locations, the analyst defines and divides the study area into traffic analysis zones (TAZ). The analyst represents the transportation network as a graph with nodes and links. The analyst references the boundary to the definitions of external trips and internal trips from the centroids of zones. Typically, the number of zones determines the complexity of the assignment problems. To systematically calibrate volume-delay functions with a full range of volume-to-capacity ratios, analysts can study characteristics of the facilities based on different traffic monitoring systems or census data; including the measurements of traffic flows, speeds, capacities, and other performance measures (Patriksson 2015).

Social-Economic Data

The social-economic data, together with household surveys and the land-use model, form the basis for developing relationships between the trips/activities and the distribution of population, employment, and other related factors. The social-economic data typically include population distribution, employment trends, economic activities, income, and car ownership.

Travel Demand Profiles

The demand database describes the day-to-day traveling movement between zones, which can include both external trips and internal trips. Covering different trip modes and trip purposes, the analyst might estimate trip sizes based on household surveys, roadside surveys, or other types of surveys.

Clustering

Clustering refers to the grouping or segmenting technique applied to a collection of objects. Objects within a cluster are closely related. Clustering methods usually use a dissimilarity measure to cluster the objects. Analysts have used clustering to select operational patterns to use in combination with traffic simulation modeling. As discussed in chapter 5, a number of efforts funded by the Federal Highway Administration (FHWA) successfully demonstrated the use of cluster analysis in simulation modeling. Although the K-means clustering method has been widely used, there are several other clustering methods, each with its advantages and disadvantages. Some of these methods are K-prototypes, K-medoids, hierarchical clustering, clustering with dimension reduction using principal component analysis, fuzzy clustering, Gaussian mixture models clustering, and clustering using Wavelet transformation, among others.

LAND-USE TOOLS

Land-use planning is upstream of the decision horizon from travel demand. MRM can also account for land use because different subnetworks sometimes have very different trip-generation characteristics. Land-use models predict future changes in population and employment based on economic theories and statistical methods (Waddell 2011). Banister (1995) divided the development of land-use modeling into roughly three generations:

- During the 1960s and early 1970s, the Lowry model had the most important impact. The Lowry model reflects gravity theory from Newton’s law. The core assumption is that the “basic” sector, including industrial, business, and administrative establishments, is exogenous to the model. This basic sector associates trip attraction with the employment of two other sectors: retail and residential.
- In the 1970s, the second generation of land-use models emerged and included microeconomic theory for building supply processes, building markets, and endogenous price information. The representations of households and other decisionmakers contain more disaggregation.
- In the 1980s, the third and current generation emerged when the integrated and semiintegrated urban models were developed. These models contain significant market representation and explicitly account for the demand, supply, and prices in land development.

The input data and process steps for the land-use models are the following:

- Parcel files—household characteristics and utility availability.
- Employment—business survey data.

- Census and public use microdata sample data.
- Boundaries—environmental, political, and planning.
- Characteristics of the highway network**.**

Outputs from land-use models include household location choice, household classification, employment location choice, employment classification, real estate development, real estate classification, real estate measure, and real estate prices.

Researchers have recognized the following limitations of land-use models:

- Land-use models usually need a larger amount of data, extensive computer resources, and an expenditure of significant planning resources. For small-scale applications, the available data, expertise, and budget may be limited to support the model's development and maintenance.

- Land-use models use a calibration process that may be difficult and time-consuming due to high data requirements and the complexity of model preparation and estimation methods.

- Land-use models need to integrate with transportation models, since transportation accessibility is an important variable on the location decisions of households. Compatibility issues may exist for the land-use models to interact with different types of travel demand models or ABMs.

CONVERGENCE

The convergence of models is an important issue for modelers to consider. The assessment of convergence is important to ensure the quality of results.

User Equilibrium in Static Traffic Assignment

In static traffic assignment (STA), a widely used measure for convergence is the relative gap, which measures the difference between the current iteration solution and the ideal solution. In the case of static assignment, where the model solves user equilibrium (UE) analytically, it is possible to define a desirable level of convergence with a very small gap (e.g., 0.01 percent).

DUE

Almost all equilibrium-seeking DTA algorithms adjust the route assignment using an iterative solution procedure. At every iteration, the model provides time-dependent link travel times from network loading for finding time-dependent shortest paths for each O-D pair and departure period (or time interval). Then the model combines the time-dependent route with the existing route set. Finally, the model redistributes flows between every O-D pair and departure time interval based on the updated set. The DTA algorithm converges when there is no substantial incentive for a user to select another alternate route, which characterizes the so-called dynamic user equilibrium (DUE) (Banister 1995). However, it is notable that there is still no agreement on convergence criteria by researchers for DTA, nor a unique formulation to evaluate the convergence in simulation-based DTA models (Hadi et al. 2016). DTA algorithms only test for convergence by calculating various metrics that measure the deviations in flow patterns or congestion indexes between successive iterations and checking whether they are less than a prespecified tolerance level (e.g., 1–5 percent), which is a measure of the amount of error (with respect to perfect equilibrium) permitted in the ultimate solution.

Feedback between DTA and Demand Forecasting Model

The importance of feedback between DTA and the travel demand model varies by project purpose, analysis context, and application. In general, if the analyst believes the scenario of interest triggers multidimensional travel choice adjustments, such as departure time and/or mode choice, then the analysis can consider an appropriate feedback framework and procedure to depict such choices. The feedback process could generally benefit from either a trip-based or activity-based model framework. The trip-based model framework takes the so-called skim data (zone-to-zone travel times) and feeds these back to various prior steps to reestimate trip generation, distribution, mode share, and/or departure time choice.

The main feedback mechanism from DTA to an ABM is the so-called skim matrices, which are the zone-to-zone (or parcel-to-parcel or location-to-location) travel times. The traffic simulation model informs these travel times. The change in travel time due to the scenario of interest could trigger the adjustment of different travel decisions.

OTHER ISOLATED MODELS

This section describes other isolated models that the agencies can use to support MRM. These models include O-D matrix estimation models, feedback between DTA and the demand forecasting model, planning level safety prediction model, and emission models.

O-D Matrix Estimation Models

The O-D matrix is an important input in transportation analysis. The matrix contains information on the number of travelers who commute between different TAZs of a region. O-D matrix estimation (ODME) is one of the most crucial tasks for transportation planners, who use it to estimate the demand patterns through sensor count and speed data on links.

Performing a traffic assignment of an O-D matrix means to allocate the demand on available routes connecting every pair of zones. ODME is the "inverse" process of the assignment problem, which is to obtain an O-D matrix that can reproduce the observed traffic counts. Planners can carefully examine the estimation results through the final assignment/loading step, especially under congested traffic conditions.

Planning Level Safety Prediction Model

A planning level safety prediction model (PLANSAFE) is intended to support and supplement some of the planning level activities in various TAZs based on historical accident data and other data types (Washington 2006).

Emission Models

The core technical foundation of all climate change policies is emission estimation, usually done through emission models. Typically, all of these models account for the various factors affecting emissions, although they differ in their modeling approach. Analysts can also categorize emission models as macroscopic and microscopic models. Macroscopic models use macroscopic or microscopic traffic flow parameters to estimate networkwide energy consumption (Vallamsundar and Lin 2011).

MRM

MRM is an integrated modeling approach where analysts jointly apply 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. Existing transportation analysis models vary widely in their implementations and data requirements. Each type of model has its own advantages and disadvantages and represents a tradeoff between scales and levels of resolutions (Sloboden et al. 2012). Microscopic models are effective at modeling behaviors of different user classes and analyzing control policies (e.g., freeway ramp metering and arterial traffic signal coordination) (Sbayti 2010). Macroscopic traffic demand forecasting models are better at estimating the spatial distribution of travelers and mode shifts (Zhang et al. 2011). Mesoscopic models can estimate regional dynamic route shifts considering traffic dynamics and queuing phenomena (Zhou and Taylor 2014). Depending on network size and the types of analyses required, all types of models are potentially valuable for transportation analysis.

Multiresolution Tool Integration

The corresponding analysis, modeling, and simulation (AMS) tools, which can address specific traffic management goals, support MRM. Nevers et al. (2013) provided a high-level overview of different domains that an AMS platform can integrate for MRM, including:

- Macroscopic travel demand models.
- Mesoscopic models.
- Microscopic models.
- Activity-based models.
- Deterministic operation models.
- Safety prediction models.
- Land-use models.
- Emission models.

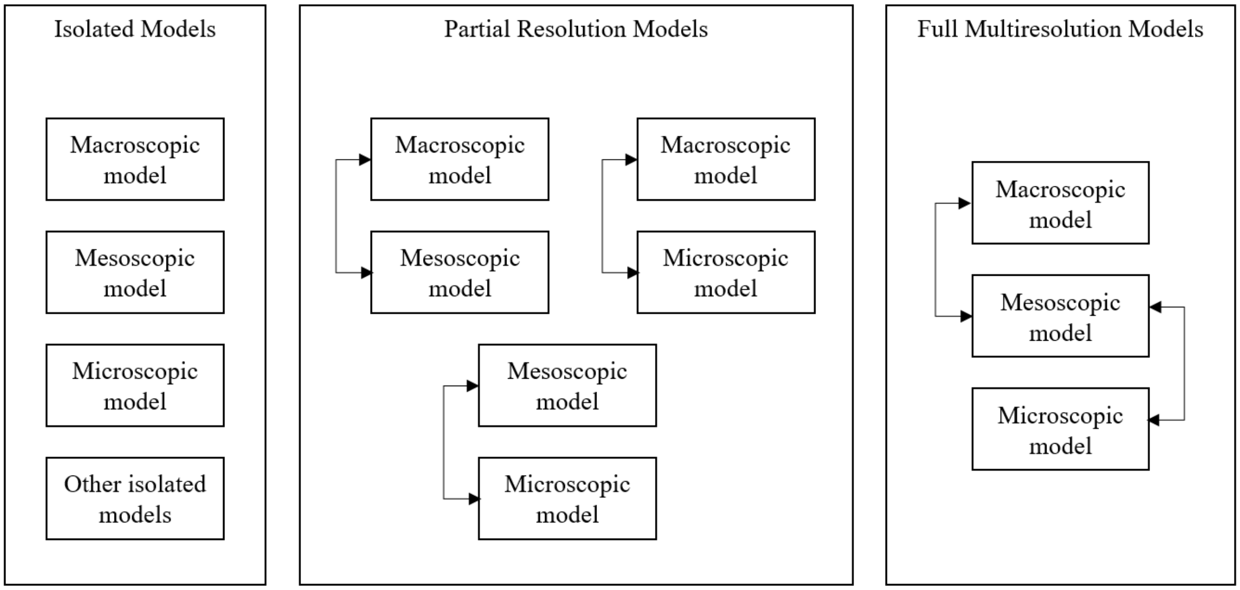
MRM methodologies usually encompass the determinant of macroscopic trip patterns, analyses of the mesoscopic impact of driver behavior in reaction to mitigation strategies, and microscopic analyses of the impact of traffic control strategies on the roadway (Sloboden et al. 2012).

Each of these independent models has inherent limitations in replicating complex system performance across different domains. Nevers et al. (2013) also listed a series of state-of-the-art framework for different types of model integration:

- Macroscopic demand model—mesoscopic DTA model integration.
- Macroscopic/mesoscopic model—microscopic model integration.
- Macroscopic model—deterministic model integration.
- Microscopic/mesoscopic model—deterministic model integration.
- Integrated Corridor Management (ICM) model.
- DTA model—ABM integration (Hadi et al. 2014; Rossi et al. 2014).

Full/Partial MRM

MRM modeling efforts can have two types of model structures. Traditionally, analysts apply each of the models independently of one another. Researchers call this an isolated model structure. Integrating two or more isolated models, such that the outputs of one model become the inputs to another, creates the MRM structure. There are two variations of MRM structure: partial MRMs and full MRMs (figure 1). Full MRM implementations integrate the macroscopic, mesoscopic, and microscopic models all into one modeling framework. Partial MRM implementations lie between isolated models and full MRMs. Partial MRMs apply trip tables generated from higher-level regional demand models to feed mesoscopic models and microscopic models, respectively (Sloboden et al. 2012).



Source: FHWA.

Figure 1. Flowchart. MRM frameworks.

Hybrid Models

The MRM structure discussed previously is an offline model integration, where each model is run to convergence and the model results are fed as inputs to another model (e.g., the trip table from a converged macroscopic regional demand model is used as input to a mesoscopic simulation). In comparison, analysts can also execute hybrid models in an online environment with streaming measurements, where two different modeling resolutions simulate concurrently in a rolling horizon framework with real-time network information exchanges (Banister 1995).

Subarea Analysis and Boundary Conditions

In a typical MRM application, the analyst creates a subarea that runs with the microscopic simulation logic and rules, while the rest of the network runs with mesoscopic traffic simulation rules. For instance, the analyst models a subarea with a complex signalized intersection microscopically while modeling the rest of the network as a mesoscopic scale at the link level. Planners address these modeling challenges due to complex interactions between demand and supply sides of the original network and the subarea network. For example, it is desirable for the model at the subarea level to retain the capability to capture changes in overall demand in the original network, while the original network model can also be sensitive to supply-side changes in the subarea (Zhou et al. 2006). A desirable MRM approach aims to provide a sound demand updating procedure for subarea analysis to maintain elaborate linkages in terms of structural information on zone, O-D, path, and link-flow patterns. Vendors and practitioners should develop data conversion tools to ensure the boundary conditions from the entire higher level network to the fine-grained subarea networks. After identifying the subarea boundaries, analysts should conduct path-based traffic assignment in the higher level network to generate path flows entering, exiting, and bypassing the subarea. Desirable network conversion should also convert zonal connectors to side streets near the subarea boundaries to facilitate a consistent subarea-based O-D estimation effort. The concepts and issues discussed in this report are also applicable to hybrid simulation.

Land-Use Model—Transportation Integration

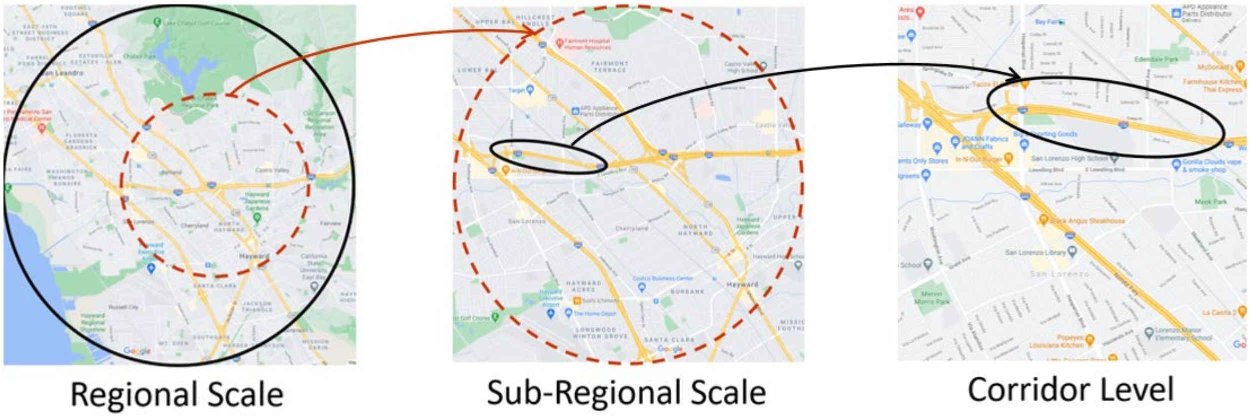
In the 1950s, researchers came to recognize the complicated interrelationship between transportation and city development (Banister 1995). One term to summarize the relationship between land use and transportation is the "land-use transport feedback cycle." Land uses such as residential, industrial, or commercial across an urban area determine the locations of human activities. The locations of facilities in the transport system create travel demand or spatial interactions between the facilities. The structure of a transport system creates opportunities for spatial interactions, which analysts can measure as accessibility. The accessibility of the traffic system inversely determines the location decisions and results in the new land-use system.

Vendors have developed integrated land-use and transportation-demand forecasting models to address the interdependence of transportation and land use (Nicolai 2012; Nicolai and Nagel 2010). Transportation planners have realized that the transportation system performance impacts land use, since accessibility is a major consideration in the selection of a residence or a business location. Improving the accessibility to and from a location will increase its attractiveness for new land development.

Dynamic Traffic Assignment—MRM Relationship

Macroscopic, mesoscopic, and microscopic simulation models can incorporate DTA methods. MRM is an effective method for linking analysis tools with different resolutions to enhance DTA. Within the MRM framework, the analyst feeds the results from one model to another in an iterative process to improve overall analysis results and maintain consistency between model assumptions. Overall, analysts can implement the MRM methodology in the following network levels (as shown in figure 2):

- Macroscopic trip table manipulation for the determination of overall trip patterns in a regional network.
- Mesoscopic analysis of the impact of driver behavior in reaction to mitigation strategies in a subregional network (both within and between modes).
- Microscopic analysis of the impact of traffic control strategies at corridor-level roadway junctions (such as arterial intersections or freeway interchanges).



Regional Scale

Sub-Regional Scale

Corridor Level

© 2021 Google® Earth™. Annotations by FHWA to show regional, subregional, and corridor-level boundaries (Sloboden et al. 2012) (see Acknowledgments).

Figure 2. Maps. Different levels of road networks.

CHAPTER 3. REVIEW OF TOOLS

Based on the modeling concepts and theories introduced in chapter 2, this chapter discusses how users commonly apply and integrate various traffic analysis tools into real-world applications. First, the chapter compares and discusses transportation analytical models and simulation models. The chapter then reviews the demand-side modeling and traffic supply-side modeling tools.

ANALYTICAL VERSUS SIMULATION TOOLS

Both analytical and simulation methods are modeling approaches that attempt to replicate the complex system performance in different conditions. Analytical tools—also referred to as deterministic tools—allow the estimation of traffic parameters and performance such as capacity, density, speed, delay, number of stops, queuing, and LOS without conducting simulation analysis. Examples of such tools are those that implement the procedures of the HCM (Federal Highway Administration 2018). These tools are suitable for analyzing the performance of isolated segments or intersections, particularly under lower congestion levels. Further, these tools can quickly predict capacity, density, speed, delay, and queuing on a variety of transportation facilities.

Analysts use simulation tools when an analytical formulation cannot be derived (e.g., when the size of the model is too large or when no analytical solution can be derived). Simulation models provide results for a specific case study and should run a long time to achieve the numerical calculations. Analysts can use simulation models to measure the performance of transportation systems and fully utilize a variety of empirical data under different complex scenarios supplied by decisionmakers.

One example to illustrate the difference between analytical and simulation tools is the DTA models. DTA models address the short-term and long-term traffic impact analyses of operational planning and strategies, and the regional traffic performance evaluation of assessing operations of subarea networks, corridors, and individual segments. There are two major types of DTA models, which help to describe the formation, propagation, and dissipation of traffic congestion in a transportation network: analytical and simulation-based DTA. Vendors built most of the existing commercially available models on a simulation-based framework because traffic-flow simulators are generally more flexible for network-flow loading than analytical DTA models in accounting for various network traffic conditions, such as traffic signals, incidents, or driver routing behaviors.

DEMAND MODELING TOOLS

Traditionally, analysts have used demand models to forecast demands for future years and thus provide inputs to models that estimate system performance for future years. Further, analysts can use demand models as sophisticated tools to forecast future multimodal demand and patterns. Demand forecasting models forecast the impacts of infrastructure improvements; transport policies; and socioeconomic, demographic, and land-use changes on transportation system performance (Patriksson 2015; WisDOT 2018). The input data of demand forecasting models include current socioeconomic data, networks, trip rates, and other factors to calculate the current and future travel patterns on a transportation system. Combined with other planning tools, travel demand models can output a variety of data, including roadway traffic forecast information and deficiency characteristics.

Network Development

The digitized network of the regional roadway system, zone centroids, and centroid connectors were developed. For MRM implementation, it is critical to develop a standard data structure to represent multiple levels of networks. Roadway inventory data (such as the number of lanes, posted speed limit, one-way or two-way facility, area type, facility type, 24-h nondirectional traffic volumes) need to be collected for each link.

Trip-Based Models (Four-Step Method)

The analytical four-step travel demand model has been widely used to estimate travel demands on current and future networks in the United States for decades (Chiu et al. 2011). It is a four-stage, sequential algorithm. When implemented correctly, information is passed from network assignment to the earlier models (vehicle ownership in the trip generation, destination choice or trip distribution, and mode choice) largely to reconcile submodel assumptions used in the prior iteration.

Trip-based models integrated with other model methods should apply a new and refined volume-capacity travel-time function. Key MRM outputs from macroscopic trip-based demand models should include summaries of trip-generation data, link traffic volumes and volume-to-capacity ratios, vehicle trip matrices for time intervals modeled, vehicle miles traveled (VMT) summary, sector volumes, and/or district-assigned volumes.

Trip-based models, also referred to as the four-step demand models, have been the dominant type of regional and statewide demand forecasting models for passenger and freight traffic for a long time. These models involve four sequential stages: trip generation, trip distribution, modal split, and assignment on traffic road networks or public transit service network. The models include the following information:

- Modeled objects: The modeled objects of the four-step method include vehicle trips (e.g., personal trips generated from households).
- Space: The network is composed of TAZs.
- Time: Each TAZ in the study area can generate and attract trips on a daily, peak-period, or multiple-period basis, depending on agency needs.

The four-step model can deal with relatively simple techniques and reasonable amounts of data. The main steps of the four-step method are as follows (Chiu et al. 2011; Hensher 2002; Patriksson 2015) (figure 3):

- Trip generation: Trip generation involves the forecasting of trip production and attraction for all TAZs based on household or workplace survey results. Models predict the number of trips on a daily or peak-period basis. The socioeconomic data for TAZs include population, number of households, household characteristics, vehicle ownership, number of children, income levels, industry employment, retail employment, service employment.

- Trip distribution: Trip distribution involves using models to forecast the (spatial) origin and destination demands between zones. This step uses the trip length frequency distribution curves derived from census data for each trip. Planners can also use the gravity model or destination choices in land-use models to derive the spatial distribution of the demand.
- Mode choice: The modal split stage applies a mode choice analysis to identify the mode share. This step predicts the percentage of trips made by different modes, such as automobiles, pedestrians, bicycles, trucks, and transit, using discrete choice models. This step commonly uses the multinomial logic model.
- Assignment: This step assigns the predicted trips between each O-D pair to actual routes through the network. A static UE assignment algorithm is typically used to identify the path between origin and destination pairs. To arrive at UE, the travel demand program provides an iterative cycle of assignments with the capability to adjust link impedance between assignment iterations.

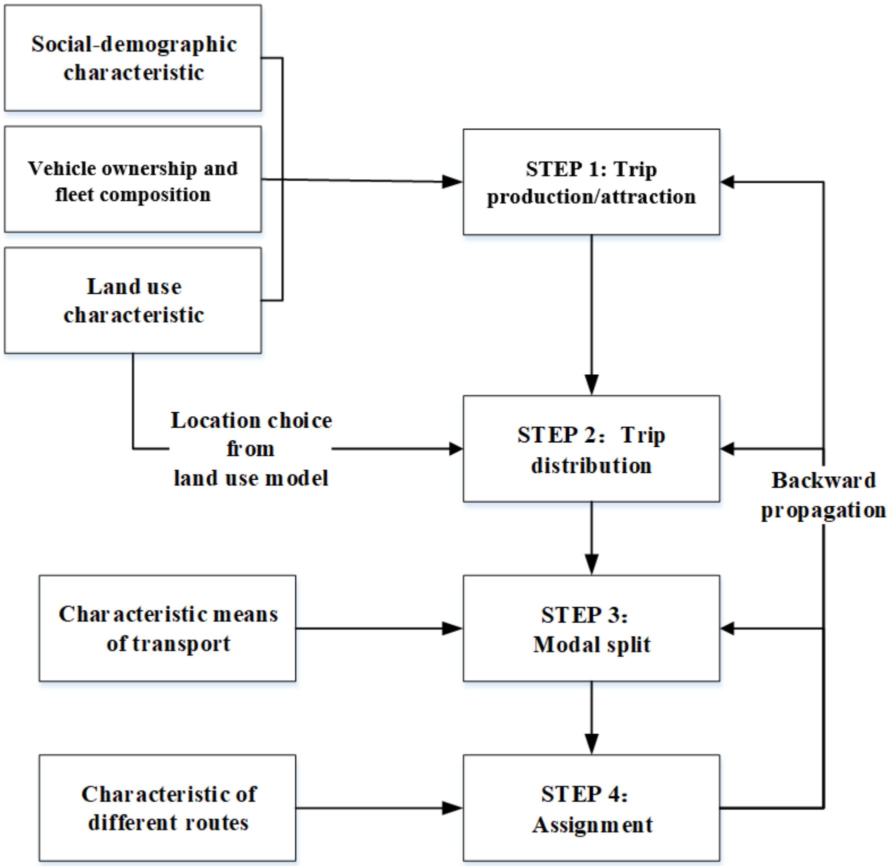


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Figure 3. Flowchart. Four-step macroscopic travel demand model scheme.

An advantage of the four-step model is that it is a feasible way to reduce the complex system of traveler behavior into analytically manageable and easily implementable components. Industry experts have long recognized the following limitations of MRM related to four-step travel demand models (Meyer 2001):

- MRM is incapable of dynamic temporal response (travel-time departure choice). Examples of where dynamic temporal response is needed include gauging network effectiveness for vehicle emissions, variable roadway pricing, flexible work hours, convertible travel lanes, or congestion responsiveness. Furthermore, because of the highly aggregate approach, four-step models do not capture travel behavior influences, such as the value of time (VOT) and value of reliability (VOR).

- Regional travel demand models frequently rely on relatively large spatial aggregation in their zone systems. Adapting these for more detailed transportation evaluations, including those of mixed-flow demand, require a much smaller zone system and accurate zone connectors to the network to reflect public streets or driveways.

- Four-step models use a static representation of time that may cover a day, four to five periods within a day, but no more refined than a 1-h demand table. Dynamic mesoscopic and microscopic simulation tools have much higher fidelity, typically on the range of 15-min or fewer increments to support sufficient demand responsiveness to properly gauge traffic operation and/or intelligent transportation system (ITS) treatments, mode of access to transit stations, and air-quality emissions.

DTA Versus STA

In general, the macroscopic demand forecasting models use STA to assign traffic to paths between origins and destinations in the network. STA typically assumes that link flows and link travel times remain constant over the modeling horizon, which normally covers all hours of the peak periods and even the whole day in some models. In comparison, DTA aims to capture travelers' time-dependent path choices as they traverse from their origins to destinations. The resulting time-varying link flows and travel times can capture more realistic traffic flow and driver responses compared to STA. DTA technologies are widely used in mesoscopic models. Microscopic models also incorporate DTA to estimate link-demand inputs.

Traffic models assess the time-dependent path performance based on measures such as travel time, cost, and even reliability, safety, and comfort. The models then feed path performances from the simulation back into the travelers' route choice components to revise the route assignment. Although analysts can potentially use any resolution of simulation with DTA, the most commonly used resolutions for relatively large networks are mesoscopic simulation and low-fidelity microscopic simulation. Sometimes analysts implement discrete choice models in conjunction with DTA to consider other travelers' behaviors, such as time-of-day choices, peak spreading, and mode choice (Ben-Akiva et al. 2002; Jayakrishnan, Mahmassani, and Hu 1994; Chiu et al. 2011; Boyles et al. 2020).

The size of model networks can vary greatly when DTA is applied. Since route choice is a major element of DTA, the size of the model network, at a minimum, could include alternative routes to allow route choice to occur. Ideally, the travel demand model for a region would stratify into peak periods or individual hours. Daily regional models (24-h assignments) are too coarse for a DTA modeling approach that examines congestion and traffic assignments at a time increment of less than 1 h.

Some DTA tools require O-D matrices (outputs of trip-based demand models). Others also accept individual vehicle activities from ABMs as inputs. The input data and process steps for mesoscopic DTA models include:

1. Demand data: Analysts can import time-dependent trip tables at a TAZ level from macroscopic traffic demand models for peak or off-peak periods. Analysts can use TAZ trip tables for multiple vehicle types or classes (e.g., car, transit, truck) and for roadway networks with multiple modes.

2. Network data: DTA requires more detailed network data than macroscopic travel demand models. These network data include the presence of acceleration/deceleration lanes, turn bays, and lane connectivity.

3. Control data: Signal timing and phasing data are critical for DTA analysis. Two common choices for signals are pretimed or actuated operations. Nonsignal traffic control options include stop control, yield control, and roundabout.

4. Scenario data: To test different scenarios, analysts can choose specific scenario parameters within DTA models.

5. DTA model process data: The iterative algorithmic procedures adjusted routes based on experienced travel time.

Outputs from DTA models include traffic conditions (e.g., LOS, speed, travel time, traffic volume on each link, VMT, vehicle hours traveled, delay, queue length, bottlenecks, and reliability) and routing decisions of travelers. The major benefit of using DTA is the capability of the modeling method to account for spatial and temporal effects of congestion and cost in determining route choice, time of departure choice, and mode choice. DTA is suitable for analyses involving incidents, construction zones, active transportation and demand management (ATDM) strategies, ICM strategies, ITS, and other operational strategies, as well as capacity-building strategies. DTA models have been an increasingly popular tool for use in subarea and network analysis. The major capacities for DTA are as follows (Chiu et al. 2011):

- **Dynamic Network Equilibrium:** This network equilibrium modeling capability is not available in static macroscopic traffic assignment and most microscopic traffic simulation models. The primary application areas for DTA models are:

    - Roadway configuration changes (e.g., change downtown streets from one-way to two-way configuration).
    - Freeway expansions.
    - City bypass construction.
    - High-occupancy vehicle (HOV)/high-occupancy toll (HOT) lane additions or conversions.

    - Integrated freeway or highway corridor improvement/construction.
    - Travel demand management (TDM) strategies, such as traveler information and congestion pricing.

- **True Capacity Constraints:** Unlike a macroscopic travel demand model's traffic assignment, in which the volume can be greater than the roadway capacity, DTA is capable of using more realistic capacity constraints on upstream and downstream system performance over time. With proper calibration, these realistic capacity constraints can enable DTA to produce more accurate evaluations of operational alternatives than a traditional macroscopic traffic assignment model.

- **Flexible Interfacing:** DTA can interface with multiple modeling domains: signal optimization, travel demand, and microsimulation models. When it comes to a complex scenario evaluation, analysts can integrate DTA with other models to perform analysis using manual techniques or customized utility functions.

Although analysts could potentially use any resolution of traffic analysis tools within DTA, the most commonly used resolution is the mesoscopic scale. Industry experts have also recognized some limitations of the DTA models, including:

- DTA models do not generate an O-D matrix and subarea network. The O-D matrix and subarea network come from macroscopic travel demand models or user input. The accuracy of the DTA models depends on the outputs from the macroscopic travel demand models.

- DTA models often have an overly simplistic representation of signal control.

- DTA models may not be able to model intersection turning movements well.

DTA is often used for regional analysis of best-case (i.e., system optimal) scenarios, worst-case (i.e., user optimal) scenarios, assessment of candidate traffic control strategies, and evacuation scenarios. In such cases—and the cases of most forms of modeling in this section—consideration of performance measures from another modeling resolution would be valuable for verifying and/or calibrating fundamental traffic flow behaviors.

Activity-Based Modeling

Analysts are increasingly using ABMs in practice to replace the four-step models. An ABM generates activities, identifies destinations, estimates the travel mode used, and predicts the network facilities or routes used. This activity is similar to what trip-based models accomplish. However, an ABM has important modeling features not available in trip-based models, including the consideration of realistic constraints of time and space and the linkages among activities and travel. ABM contains a set of discrete analytical models of household travel. Thus, an ABM works at a disaggregate person level rather than the more aggregate zone level, as in the trip-based models, and can better account for various person-level and household-level attributes. For example, an ABM can provide better capabilities and sensitivities for evaluating pricing scenarios at the person level. In the United States, conventional travel demand models are slowly moving forward to the new generation of behaviorally realistic activity-based models.

Activity-based simulation is a discrete simulation that represents the components of a system as they proceed from activity to activity. An example of an activity-based simulation is one in which a manufactured product moves from station to station in an assembly line (Army Modeling and Simulation Office 2020). The main characteristics of ABMs versus conventional travel demand models (trip-based models) are as follows:

- Modeled objects: ABMs may be used to model households, travelers, schedules, or trips.
- Space: Typically aggregates parcel data to larger microzones that are smaller than TAZs used for trip-based models; the higher fidelity is helpful for modeling walking trips and transit access in dense urban areas.
- Time: Typically, 27–30 h at 15- 30-min resolution. The extra time beyond 24 h buffers travel at the beginning and end of the model day.
- Application: ABMs can represent prior-observed travel demand or estimate travel demand for unobserved scenarios.
- Tour-based models versus trip-based models: A tour is a closed chain of trips starting and ending at an anchor location. The tour-based model records trip dimensions (e.g., mode, destination, and time of day).
- Dynamic models versus aggregate approach: Analysts can use microsimulation or detailed mesoscopic models in conjunction with tour-based model outputs. It is inappropriate to apply a tour-based model using an aggregate approach because of the difficulty of capturing internal sensitivities for individual population and travel segmentations. There are a few examples of dynamic travel simulation models in research and no examples in practice (Xiong 2015; Zhang et al. 2011).

The input data and process steps for ABMs are:

- Parcel attributes: jobs and school enrollment by type, households, housing stock, parking by type, and distance to transit by type.
- Skim: the shortest-path TAZ-to-TAZ travel cost matrix.
- Zonal/parcel data: includes employment, school enrollment, housing units, and network attributes.
- Detailed census/house survey data includes the following information:
    - Household: location, size, and vehicles.
    - Person: age, gender, usual work, and school locations.
    - Day: purpose, destination, timing, main mode, and the number of stops.

  - Trip: origin, destination, origin purpose, destination purpose, mode, departure time, and travel time.

The activity-based microsimulation model typically provides direct outputs at different resolutions. Generally, the outputs include the disaggregated activity schedules (i.e., trip chains) of different household members based on their individual travel requests along their trip chains. Alternatively, analysts can format the outputs as time-dependent O-D matrices by aggregating individual trip chains using a trip aggregator. In current practice, analysts feed these outputs as inputs into the mesoscopic simulation with finer departure and arrival times for individual trips. These outputs can be inputs to the mesoscopic simulation with more precise departure/arrival time and spatial resolution.

The major advantages for ABMs over conventional four-step models are as follows (Zhang et al. 2011):

- Travelers in ABMs are constrained by prior choices, time, and space over the course of the model day. The activity-based model is fully consistent in modeling time-of-day choices. In the trip distribution step, the model associates non-home-based trips with the location of home-based trips on the same tour. In the mode-choice step, the chosen model is consistent in the tour, not for each trip.

- Pricing and congestion responses in ABMs are conditioned/constrained by strategic factors, such as picking up dependents or flexibility in arrival time at work. In the determination of trip productions, activity-based travel patterns consider numerous interrelationships, tradeoffs, and substitution effects between different tours in time of day.

- Trip departures have higher fidelity scheduling information available for other models, such as DTA. In practice, this information tends to be at a resolution of 30 or 15 min.

- Activities occurring daily are sensitive to the travel environment and accessibility. In the trip attraction step, the model organizes destination-choice size variables by activity type and their primary/secondary role in the tour-based model structure.

- Data requirements for ABMs are not fundamentally different than those for conventional four-step models. The most significant data need is disaggregated travel diary information obtained from home interview surveys. Analysts must design survey questions carefully to fit within the activity-based modeling framework (Castiglione 2015).

Researchers have recognized the following limitations of the ABMs (Zhang et al. 2011):

- The network assignment software implements network assignment procedures in the same manner as the four-step models. The software converts and aggregates outputs of an activity-based and tour-based microsimulation model into a conventional trip table for trip assignment.

- The relatively complex and time-consuming process of developing a new activity-based model is an obvious disadvantage to practitioners and agencies. Successful demonstrations and improved forecasting accuracy of ABMs are necessary.

Deterministic Analytical Models

The analytical/deterministic tools can quickly estimate different attributes of links (e.g., capacity, speed, density, and queuing) of different facility types. The tools reflect the procedures provided in the HCM and provide useful ways for analyzing the performance of isolated and small-scale transportation facilities (Federal Highway Administration 2018).

Microsimulation

Analysts use microsimulation tools to simulate the impact of certain demographic and policy changes on individual (i.e., microscopic) agents. In transportation modeling, microsimulation tools can track the highly detailed movements of the vehicles (or agents) in the lane/cell-based microscopic network, such as highway traffic flowing through an intersection or lane changes closing to ramps. Microsimulation captures interactions between multiple agents by considering their behavior characteristics and allows "what if" testing of various decisions (Federal Highway Administration 2018).

SUPPORTING TOOLS

As modeling methods and tools advance and become more sophisticated, there is an increasing need for additional tools to support the modeling activities. For example, AMS tools can help process required data, support the connections between data sources and modeling tools, support conversions between modeling tools, process the outputs, and support other modeling processes.

Data validation and data cleaning are extremely important steps to take before using the data for analysis. There is a need for integrated data tools that allow the extraction, fusion, archiving, and processing of real-world data. There is also a need for conversion support to help convert real-world data to a format useful for modeling and to convert input and output files from one format to another depending on the specific modeling tool used. Researchers have also used time-dependent demand estimation tools based on combinations of demand forecasting model outputs and real-world data. Other useful tools include statistical tools that can perform clustering analysis to group traffic into different patterns to allow multiscenario modeling and those that provide statistical analysis support and visualization of the results.

Some research has focused on solution convergence properties of the integrated system and has specifically examined different criteria for convergence. Findings have included several technical issues related to model integration. For example, researchers have studied how to convert activity travel patterns in continuous time to dynamic O-D matrices for DTA and how to extract time-dependent traffic link volumes and speeds for the activity model (Xiong 2015, Xiong, Zhou, and Zhang 2018; Zhang et al. 2011).

In order to support convergence analysis, the supporting tools should allow the user to visualize the variation of the convergence criteria with respect to the iteration number. Also, the tools should list the top links with the largest deviations in link volumes between two consecutive iterations when link-based criteria are used or identify the O-D paths with the largest differences in path travel time or generalized costs between two iterations for path-based convergence analysis. Such information can help users examine model convergence and quickly locate the critical links or O-Ds that affect the convergence of the model (Banister 1995; Hadi et al. 2016).

SUMMARY

This chapter aimed to assist traffic engineers and planners in the selection of suitable types of traffic analysis tools for specific operational improvements and modeling needs. The chapter also intended to help practitioners understand how to integrate existing analytical and simulation tools to create a cost-effective MRM application in the next step.

CHAPTER 4. SUMMARY OF STATE-OF-PRACTICE OUTREACH

This section presents a summary of research team findings based on conversations held with users and vendors of MRM tools. Overall, the team held 14 teleconferences with experienced MRM users and developers. Of these discussions, four involved the tool vendors. The team used the following questions in the discussions with public agencies and consultants:

- How do you define MRM?
- How many MRM projects have you conducted, are you involved in, or do you know of in your State/region?
- How have you implemented MRM?
- How much effort does it takes to set up an MRM?
- What are the size limits of your MRM?
- What are the benefits and costs of MRM?
- What are the barriers to applying MRM?
- What defines your hesitation to apply MRM?
- What is your agency’s interest level in MRM?
- What will be the short-term and long-term impacts of MRM?

The team used the following questions in the discussions with the software vendors:

- How do you define MRM?
- What MRM advertising do you have?
- How important do you think MRM is?
- What MRM case studies do you have?
- What MRM features (e.g., feedback, convergence) do you currently offer?
- What is your company’s interest level in MRM?
- What MRM features are you planning to develop?
- What interest level in MRM do you perceive from your customers?
- Can you provide any documentation or guidance related to MRM models in your tools and the implementation of these models?

MRM DEFINITION

Most participants in these discussions gave the commonly used definition of partial MRM, full MRM, and hybrid simulation, as presented in chapter 2 of this document. However, this section summarizes some of the variations of these definitions.

Subarea Macroscopic Modeling

Some of the participants mentioned that there is another level used by the modelers that fits between the demand-forecasting model and the mesoscopic simulation or microscopic simulation model. This additional level involves the modeling of a refined subarea network in an STA tool that uses a macroscopic traffic flow model. The subarea refinement includes an update/correction to the geometry; addition of geometry detail, refined zones (possibly disaggregated), and zone connectors; as well as intersection signal timing. The modelers use the output from this network in developing inputs to the more detailed level of modeling. In most cases, the modelers used this subarea model for the static assignment of traffic to produce inputs to microscopic simulation models. In few cases, modelers used such subarea models in combination with an ODME procedure to produce O-D matrices used as inputs to mesoscopic simulation-based or microscopic simulation-based DTA.

Sometimes MRM users refine the subarea macroscopic model in a different tool than what they use for the regional demand forecasting model to take advantage of the additional flexibility provided by the utilized tool. Another point users mentioned is that there are different levels of mesoscopic models that vary in their capabilities and run times. For example, some of these tools are link based, while others are lane based.

Subarea Microscopic Analysis to More Detailed Microscopic Analysis

An MRM user in Maricopa County, AZ, implemented another variation, which was a microscopic simulation model developed at the County network level. This variation allows for the refining of the subarea or corridor networks of the model as needed for specific projects for more detailed analyses. The authors suggest describing such a framework as regional model macroscopic to subarea microscopic to more detailed microscopic analysis. The Maricopa County, AZ, MRM user reported that such a framework reduced the time to conduct the subarea or corridor analysis from weeks or months to days.

ABMs to DTA

Another major variation is the direct integration of demand-forecasting models (mainly ABM) with mesoscopic simulation-based DTA. Such integration requires feedback of the path performance (skim matrices) from the simulation-assignment model to the ABM. With such an application, the MRM user must code the regional network in a DTA tool, which can be a major effort. However, agencies have reduced this effort to a degree by coding the core city or areas of interest in a high level of detail with lower levels of details for other parts of the networks. The analysts then can use microscopic simulation analysis to model subareas extracted from the regional DTA model. Examples of such implementations are the San Francisco Bay Area model[1] and the Second Strategic Highway Program (SHRP 2) C10 implementations in Atlanta, GA, and Ohio (Smith et al. 2018).

Top-Down Modeling Versus Utilizing Feedback Loop

A few of the participants realized that there are two variations of MRM. The most common is the top-down approach, going from a macroscopic modeling detail to a mesoscopic or macroscopic modeling detail in partial MRM or going from a macroscopic model to a mesoscopic model to a microscopic model. MRM users have not applied the feedback loop in the other direction, and there were no instances of such feedback reported in the discussions.

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[1] Castiglione, Joe (San Francisco County Transportation Authority); phone interview conducted by Mohammed Hadi, Xuesong (Simon) Zhou, and David Hale (research team) in the spring of 2020.

MRM SIZE AND REQUIRED EFFORT

A large proportion of the current MRM implementations are for subarea or critical corridor implementations for specific project assessment. However, there are a number of regional-level implementations of MRM. In general, these implementations have used a lower level of modeling detail for arterials and for segments outside the areas of interest. Most of these implementations were for the peak periods. However, at least one agency converted its model to 24-h modeling, eliminating the need for the warm-up and cool-down periods.[2] There was a mention of the need to start small to get some experience with these models.

Participants reported significant efforts to set up a full MRM, compared to just going from the demand forecasting model to facility-level microscopic simulation. The required effort is a function of the size of the network, the need for signal timing coding, the availability of signal timing data in a consistent format for the region, and the level of detail and correctness of the demand-model coding. Coding a midsize network in mesoscopic DTA integrated with microscopic simulation requires several months of project teamwork, based on inputs provided by agencies that have had experience with these models. The integration of ABM with the traffic simulation/DTA model requires 1- to 2-yr projects. Such integration appears more feasible for small to midsize cities.

On the other hand, participants reported that microscopic simulation for a larger network, even without the use of full MRM, takes an extremely long time to calibrate and to run. Some agencies may still not be comfortable with mesoscopic simulation, although such modeling can reduce the effort significantly.

INTEREST, BENEFITS, AND COSTS OF MRM

All of the participants indicated significant interest in MRM and this project. However, the research team expected this response, because the stakeholders selected, in most cases, had already used MRM. Discussions with the tool vendors indicated that the general level of interest did not appear to be high.

MRM allows realistic representations of traffic dynamics for a larger size network. The greatest interest appears to be due to the ability of MRM to capture changes in strategic traveler behavior in response to traffic management and demand management policies and strategies, such as managed lanes, congestion pricing, and bus rapid transit (BRT). The authors expect interest in this capability to increase with the need for modeling emerging with connected and automated vehicle (CAV) technology, multimodal operations, micromobility, mobility as a service (MaaS), and ride hailing. Some participants believe that such models produce results that make more sense, and are more defendable, compared to current modeling practices. Current modeling practices use demand forecasting model results to produce inputs to microscopic simulation models without using a simulation-based DTA level. MRM users expect including a mesoscopic simulation-based step to provide better demand development and quality control. Agencies also reported finding value from bringing probe data to provide O-D data to improve the models. In many cases, the additional costs are justified since these costs are still small fractions of the costs

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[2] Castiglione, Joe (San Francisco County Transportation Authority); phone interview conducted by Mohammed Hadi, Xuesong (Simon) Zhou, and David Hale (research team) in the spring of 2020.

of the evaluated construction projects. One should recognize that there is also a large cost associated with using the wrong tool leading to the wrong decision. However, the justification of using the tool may be on a case-by-case basis. Agencies can consider MRM primarily when the area has projects that justify such advanced modeling and when the agency has resources adequate for this effort. The cost is still a small fraction of big project construction. In particular, simulation-based DTA is useful when assessing strategies that affect the strategic behavior of travelers, such as express lanes, toll/pricing strategies, and transit improvements. Such utilization is also useful in assessing the impacts of transportation system management and operations (TSMO) strategies such as incident management, ICM, and the impacts of emerging CAV technologies and applications. Simulation-based DTA focuses on the strategic behavior of route selection. However, analysts can combine such tools with other models to estimate other behavior parameters like time shift and mode shift.

An important reported benefit of building a large-scale MRM model is that building, archiving, and maintaining such a model allows the agency to reuse it for multiple applications in the future, thus potentially reducing future modeling costs. As such, the agency develops the MRM model once but uses it many times. Analysts can then make refinements at the individual project level to the master model to improve the model.

As travelers have started using travel information apps, traffic has become more dynamic, with the routes changing potentially every 15–30 min. Thus, using static assignment for the whole peak is becoming even less adequate. Transportation network companies are producing more trip chain-type activities that motivate the integration of simulation-based DTA with activity-based models to model adequately. Another important reported benefit is the possibility of integrating MRM with air-quality models for better estimation of pollutant emissions and the potential of estimating equity measures. Outputs from mesoscopic or microscopic models can then inform the use of emission estimation models.

MRM BARRIERS AND HESITATION

Most of the users and vendors reported that the lack of experience, background, and training are major barriers to the use of MRM. There is a critical need for workforce development in this area. Participants mentioned that the current modelers belong to one of two distinctive groups. Demand forecasting modelers are generally strong in strategic behaviors but not strong in the concepts of traffic-flow theory. Microscopic simulation modelers are the opposite. Agencies could fill this gap through training.

There are also variations in the level of interest in MRM. There is an opportunity for better messaging of the value of MRM, and the associated issues, since there are many unknowns and uncertainties surrounding this type of modeling. Case studies and success stories could be quite helpful. MRM usually requires relatively great effort, time, and resources compared to current practices. Thus, messaging, case studies, and reporting lessons learned are essential to reduce the risks associated with MRM. Longer run times are also a source of hesitation.

There is a need for more supporting tools to increase the automation of data conversion and output processing. Analysts spend a significant part of their required effort on data collection and integration. For example, a city may have 5,000 traffic signals. Importing the timing for these

5,000 signals, which may be stored in different formats, can be an intensive effort. There is also a need for more integrated tools.

Maintaining adequate expertise in the concepts and the tools used in the region is a challenge. The agency and its consultant need access to the software. Thus, the costs and building experience in multiple software platforms can be a barrier, especially for smaller firms. Even progressive agencies may struggle to review MRM work. It is not easy to keep skills fresh when an agency only requests simulation-based DTA every 2–5 yr. Public sector agencies reported that there is a need for assistance from consultants and academia.

Another issue is that some agencies prescribe the use of volume development methods and procedures in their States and regions. These standards in their current forms preclude the use of a DTA-based model to forecast demands. Such agencies are reluctant to change.

Agencies and consultants sometimes do not estimate budgets and required resources correctly. Without adequate budget and resources, the MRM work will not be successful.

Another issue with large-scale MRM is the need to continue maintaining the model to include updates to land use and geometry. This issue becomes clear when the agency updates the base year in the demand forecasting model every few years. In this case, the agency may need a major effort to update the large-scale MRM.

In MRM, there is also much room for improvement with multimodal modeling. These improvements include the modeling of single-occupancy vehicles, HOVs, public transportation, micromobility, MaaS, ride hailing, and other modes.

SHORT-TERM AND LONG-TERM IMPACTS OF MRM

Most participants said that demand forecasting models with static assignment will continue to be in use for a long time. However, the participants expressed confidence that agencies will develop MRMs for each region in need of such modeling and will use these as an important part of the modeling process. Several participants expressed the opinion that, in the short term, things will not change much, although more agencies will use MRM to support decisionmaking. However, with time, people will better understand the benefits of MRM and will develop or acquire the workforce and resources required to build such models. The participants expected that software vendors will develop better capability, including better tool integration, consistency and convergence checking, and data processing and fusion. Parallel processing could allow different computers to run different parts of a network, improving the run-time performance.

VENDOR DISCUSSIONS

The discussions with the software vendors identified many of the issues reported in the previous section based on the industry (user) discussions. Additional highlighted points in the vendor discussions include:

- MRM has the advantage that analysts can use the results from macroscopic simulation or mesoscopic simulation as inputs to lower level (higher resolution) models. Analysts can also use the initial assignment results as a warm-up to the assignment in the lower level.

- Vendors found that MRM and hybrid simulation are hard to sell, and there is a need for more research and demonstrations.

- "Stovepiping" is a problem between the modelers of different resolutions. In many cases, they do not understand the modeling at the other level(s).

- Vendors identified the need to determine the appropriate level of fitting to real-world data, given the daily variation in the real-world data.

- Network size was mentioned by at least one vendor. If the size of the network is manageable, microscopic simulation-based DTA is sufficient, and there is no need to go to mesoscopic simulation. This statement represents the vendor point of view and not the research team's view.

- Development of a regional MRM could promote modeling consistency and efficiency in the region, as smaller subareas or corridors are extracted and modeled based on the larger-scale DTA model.

- One potential use case of the feedback is feeding turn-level capacity from microscopic simulation to upper-level simulation.

- Areas for potential further tool development may include more integration of different levels in a single tool supporting all levels of detail, file-size enhancement, cloud-based solutions, multiuser file access allowance, and better signal control consideration.

CHAPTER 5. LITERATURE REVIEW

This chapter presents a review of the literature related to MRM. The research team compiled the information based on its review of journal papers, final project reports, and guidance on the subject. The chapter presents the review in five subsections as follows:

- Guidelines, Pilots, and Proofs of Concept: This subsection presents a review of documents that provide guidelines, frameworks, and pilot testing/proof of concept of multiresolution simulation.
- Feasibility and Benefits of MRM: This subsection reviews studies that examine the effectiveness and benefits of MRM.
- Consistency of Multiresolution Models: This subsection summarizes studies that addressed consistency and achieving convergence between different levels of multiresolution models.
- Developments to Support MRM and Hybrid Modeling: This subsection reviews developments that support effective and efficient application of MRM and hybrid modeling.
- Applications of Multiresolution and Hybrid Modeling: This subsection includes a review of the applications of MRM in real-world projects or in demonstrating the effectiveness of MRM to model specific applications.

The chapter presents information for each of the reviewed studies in the following structure, if available:

- Overview.
- Implementation descriptions.
- Lessons learned.
- Benefits and costs.

The end of the chapter presents a summary of findings from the literature review.

GUIDELINES, PILOTS, AND PROOFS OF CONCEPT

This section presents a review of documents that provide guidelines, frameworks, and pilot testing/proofs of concept of multiresolution simulation.

Second Strategic Highway Program C10 Dynamic Integrated Model System

Overview

The SHRP 2 funded two projects to assess the integration of ABMs and traffic simulation-based assignment models. The effort used open-source tools to build integrated models in three urban areas: Jacksonville, FL; Burlington, VT (Project C10A) (Resource Systems Group et al. 2013);

and Sacramento, CA (Project C10B) (Rossi et al. 2014). The SHRP 2 program explored the integrated modeling in Project C10, recognizing that most travel forecasting models used are not sufficiently sensitive to the interaction between travel behaviors, demands, and network/supply. Thus, they are unable to evaluate advanced demand management strategies and policies adequately.

Implementation Descriptions

Project C10A

Project C10A integrated an ABM tool, simulation-based assignment, and an emission and fuel consumption estimation model. The project team implemented the integrated model system in two regions: Burlington, VT, and Jacksonville, FL. The team investigated the impacts of pricing policies, capacity enhancements, transportation system management (operations) improvements, TDM policies, and greenhouse gas reduction strategies. The integration between the activity-based travel demand forecast tool and microsimulation tool was a partial two-way interface. DaySim (ABM tool) provided primary demand input to TRANSIMS router and microsimulator (Chiu et al. 2013; Troy et al. 2012). The DaySim activity file fed into TRANSIMS included information on each individual's activity locations, timing, and mode of travel. TRANSIMS generated zone-to-zone network impedance measures by detailed time of day to achieve better demand simulations in DaySim. The project used the Motor Vehicle Emission Simulator (MOVES) to estimate emission and fuel consumption on a mesoscopic or county level (Chamberlin et al. 2011). The integration between MOVES and TRANSIMS provided the needed input for MOVES using TRANSIMS Speed Bin and Link Delay datasets.

Project C10B

Implemented in Sacramento, CA, this project integrated a mesoscopic simulation-based DTA (DynusT) and a dynamic transit assignment (FAST-TrIPs) package (Chiu et al. 2013). The partial integration provided tour and trip rosters and trip tables from the DaySim ABM tool as input to DynusT. The rosters included origin and destination of each trip and simulated VOT, among other relevant traveler information. The research team then obtained travel time from DynusT and FAST-TrIPs and fed those data back as input to DaySim, operating a two-way interface model. The team developed a fine-grained integrated method that links an emission mode to the mesoscopic simulation model at the individual roadway link level. The team also developed a method for including reliability in the analysis. The team analyzed five alternative policies: extending transit service coverage, improving interchange design, providing freeway bottleneck relief, increasing transit frequency, and deleting a well-used bus line.

Lessons Learned

The C10A research team pointed out that the use of the integrated model system is most valuable when assessing alternatives that cause regional changes in travelers' choices. The team identified critical challenges with integrated modeling as part of project C10A, including that the availability of required data varies by region and that the run times of these models can be excessive. The team identified a need for detailed model inputs to produce accurate forecasting of future conditions. Other identified issues related to the integrated model convergence and questions about the result of the validation and sensitivity analysis. Specifically, some improvements, such as roadway pricing, required regional-scale analysis that can result in excessively long run times while adding little policy-specific sensitivity.

Considering the modeling requirements and runtime considerations, the project team developed three levels of modeling details of the integrated model: planning, operations, and planning plus operations. Project C10A also pointed out the long time required to edit and debug the network extracted from the demand model. This editing and debugging included an iterative process for evaluating, adjusting, and testing the network through simulation runs. The project team stated that it faced numerous challenges when attempting to simulate the future year or alternative network scenarios, but it did not list these challenges.

The C10A final project report pointed out the need for network convergence and equilibration convergence strategies and criteria to ensure effective alternative analysis, which may be different from what is acceptable to the DTA community. The report identified as an issue the schedule consistency between what is calculated by the ABM, what results based on the congested travel time from the mesoscopic simulation tool, and what is recommended using this consistency as another measure of the quality of the model.

For the C10B project, the research team pointed out that the actual value of the integrated model is its sensitivity to policy variables. However, the research team stated that a central issue was the limited validation of the model with some significant differences between the results from the model and the existing regional demand forecasting model and real-world demands. Another issue was the level of convergence achieved in the DTA model, which affected the evaluation of the test results. It was found that after running the integrated model iterations, the systemwide model convergence "reached a plateau that did not improve with more iterations." Another reported issue was that, due to the project schedule, each model run was executed only once rather than multiple times as recommended to deal with stochasticity and noise.

Reported Benefits and Costs

The C10A and C10B projects pointed out the unique capabilities of the integrated model to assess policies that cause regional changes in traveler behaviors such as pricing, TDM, and transportation system operations and management. These models are more sensitive to such policies and strategies than traditional travel demand forecasting models. The models have a detailed representation of the system dynamics and increased behavioral and spatial detail. In addition, the model produces a broader range of statistics not available from the traditional models to support the decisions.

SHRP 2 Implementation Assistance

Overview

The FHWA SHRP 2 Implementation Assistance Program (FHWA 2020) provided funding to four C10 pilots and one adopter to evaluate integrated ABM and DTA models, considering the lessons learned from the SHRP 2 C10A and C10B projects mentioned in the previous study review (Smith et al. 2018). The use of ABM, instead of O-D matrices, in combination with DTA allows for the consideration that the VOT may be different for different travelers, resulting in different route and departure time choices. The DTA tools produce time-specific network performance data and feed these back to the ABM, allowing better estimation of the choices.

Smith et al. (2018) reported that the SHRP 2 Implementation Assistance Program evaluated the funded projects using the Technology Readiness Level (TRL) framework that initially supported the FHWA Exploratory Advanced Research Program (Deshmukh-Towery et al. 2017). This use of the TRL framework allows documenting and communicating the maturity of the research, determining the relationship to other research, and the steps to advance research maturity. The pilot projects included:

- Two pilot projects in Atlanta and Columbus, OH, that integrated ABM with DTA (Smith et al. 2018).
- One pilot project that demonstrated the value of combining agent-based models with DTA and combining ABMs with DTA in Maryland (Zhang 2017).
- Two pilot projects in San Francisco County and Puget Sound Regional Council (PSRC) to implement the dynamic transit passenger assignment model (Zorn and Sall 2017).
- One pilot project that used the reliability methodology developed as part of the SHRP 2 C04 project in the San Diego, CA, travel demand model (Dhakar et al. 2017).

Implementation Descriptions

Atlanta and Columbus, OH, Implementation

The two implementation cities used the same integration framework of an ABM model with a mesoscopic simulation-based DTA model. The Columbus, OH, implementation involved extracting the Columbus downtown area from the demand-forecasting model and producing inputs to the DTA model. Atlanta developed a mesoscopic simulation-based DTA model based on a geographic information system (GIS) file. The project team used default timings for most of the 5,000 coded traffic signals but used real-world signal phasing and timing for selected corridors. The team used the Atlanta model as part of a before-and-after study of the I–85 bridge closure in Atlanta. As discussed below in the lessons learned section, the two models used individual vehicle trajectories as a disaggregate replacement for skims and used an individual schedule adjustment module. The evaluation put this project development maturity at level 5, or integrated components demonstrated in a laboratory environment.

Maryland Implementation

This implementation involved the comparison of two approaches. Each approach involved the integration of two models. The project team proposed an initial approach for use in long-range planning that focused on improvements that have long-term impacts. This approach involved the integration of the regional ABM model with an existing statewide mesoscopic simulation-based DTA model. The second approach involved the integration of the mesoscopic simulation-based DTA model with an agent-based demand model with the DTA model mainly used for its simulation, rather than routing, capabilities. The team recommended this second approach to assess TSMO and pricing projects in Maryland. The evaluation concluded that the ABM and

DTA integration is at a level 6–7 of maturity, where level 6 is a prototype demonstrated in a relevant environment, and level 7 is a prototype demonstrated in an operational environment. The agent-based DTALite (Zhou and Taylor 2014) model integration is at level 5, or integrated components demonstrated in a laboratory environment.

FAST-TrIps Implementation

This effort explored the use of the FAST-TrIps tool for dynamic transit passenger assignment component considering transit service quality and capacity changes. The project team integrated the San Francisco County and PSRC ABM models with the goal of assessing transit-related projects in the Bay Area and Puget Sound regions. In general, the model assessment showed a lower level of maturity compared to the other two implementations mentioned preceding paragraphs. The evaluation put this project development maturity at level 3, proof of concept.

Lessons Learned

The project review panel identified a need to outline the questions that the developed integrated models can better address, comparing the results from these models with those from a traditional model and distinguishing run-time and convergence criteria for the models. As expected, the pilot projects had to deal with the additional information required for a DTA model compared to traditional demand models, including adding network and intersection control details. This additional information required a significant manual effort. Recommendations to address this issue include the use of multiresolution networks, the use of default signal phasing/timings for most locations, and the creation of a link between signal optimization tool files and the DTA models. The team expects that the ongoing data standardization efforts will help reduce the required effort.

Another major issue the projects identified is that the network loading under the more detailed traffic simulation requires realistic zone connections to the network. In most cases, the connectors in the utilized demand forecasting models are artificial links connected to a major intersection. The project panel recommended connecting several links to each zone to emulate the traffic entering from side streets, driveways, and parking lots. The identification of the temporal distribution of the demand within each period is also important.

Another major issue found in the integration of the ABM and DTA was when using the performance of the links/paths resulting from the DTA model as inputs to the ABM. The project panel found that using the resulting congested travel times may lead to schedule inconsistency (e.g., vehicles arriving unreasonably late to work). The project team addressed this issue by developing a tool for adjusting schedules to prevent this violation. In addition, another approach was used to address the fact that the disaggregate nature of the demands in the utilized models results in a large number of combinations of origin/destination, departure time interval, and traveler value of time. This large number of combinations made the use of conventional skims impractical, so the team used a combination of skims and individual trajectories.

The Maryland project noted that the DUE usually used in DTA tools could result in excessive computational time (Zhang 2017). In addition, in a real-world environment, it may not be possible to reach convergence, especially during temporary disruptions like incidents. Thus, the project team used behavior user equilibrium as part of a multiagent model. This multiagent model assumed travelers to be intelligent agents who make choices, including route, mode, and trip time choices, based on the utilities of the different alternatives. The Maryland project used this approach to predict travelers' response to operational improvements, new development patterns, or new toll roads. The team did not use this approach for long-range planning. Instead, they used DTA combined with ABM.

The dynamic transit assignment effort also faced several challenges. A large number of options were available to each traveler in time and space, making the assignment challenging. In addition, several other characteristics of transit make dynamic transit passenger assignment difficult. Based on the Atlanta implementation model results to evaluate bridge closure impacts, it appears that only changing the route choice is not sufficient to assess the impacts. The researchers recommended future modelers consider also changing the trip start time. The Atlanta and Ohio projects noted the excessive run time and that such models are more computationally feasible for small regions.

Reported Benefits and Costs

The project demonstrated that the tools used were successful in predicting how travelers adapt new travel patterns in response to system changes that are difficult to predict using ABM-STA integration. Such modeling is effective in estimating the impacts of temporary capacity disruptions and TSMO projects, including those related to pricing, dynamic lane control, ramp metering, and incident management. Other applications include the effects of new land uses, analyzing a BRT corridor, and analyzing a road diet. When the model results were validated, the Maryland project reported 10 percent freeway-volume accuracy, 15 percent arterial-volume accuracy, and 20 percent travel-time accuracy.

Traffic Management Testbeds

Overview

FHWA initiated the *Analysis, Modeling, and Simulation (AMS) Testbed Framework for Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) Programs*"(Yelchuru et al. 2017; Vasudevan 2013) to investigate the use of modeling tools and methods to evaluate the impacts of DMA and ATDM. The project team selected six testbeds to test the ATDM and DMA AMS concepts: San Mateo, CA; Dallas, TX; Pasadena, CA; Phoenix, AZ; Chicago, IL; and San Diego. The testbeds varied in their geographic scope, modeling tools, modeled applications, and the addressed issues. The efforts emphasized the importance of multiresolution analysis. In addition, on the supply side, the effort emphasized the need to model changes to network supply and capacity between days (e.g., due to incidents). On the demand side, an important focus was on capturing the changes in demand patterns between days and the changing traveler behaviors' response to management activities. The effort also emphasized the importance of capturing the dynamic interactions between supply and demand. All testbeds used clustering analysis as an important component to determine various analysis scenarios.

Overall, the simulated DMA applications in the project were speed harmonization, advanced traveler information, queue warning, freight advanced traveler information, cooperative adaptive cruise control, dynamic transit dispatch, incident zone alerts, dynamic ridesharing, intelligent traffic signal, and freight dynamic route guidance. The simulated ATDM applications were dynamic shoulder lanes, dynamic speed limits, queue warning, adaptive ramp metering, dynamic junction control, dynamic traffic signal control, predictive traveler information, anti-icing and deicing operations, dynamic HOV, dynamic managed lanes, dynamic routing, dynamically priced parking, emergency parking, preemption for winter maintenance, and snowplow routing.

Implementation Descriptions

Phoenix Testbed

The Phoenix testbed focused on the Tempe, AZ, area, which covers about 40 mi^2. The simulation used a mesoscopic simulation-based DTA tool combined with a commercially available microscopic simulation tool. Agent-based modeling was also used to assess the EnableATIS DMA. The development integrated the DTA tool with the microscopic simulation in a hybrid-modeling framework, in which a part of the network runs in mesoscopic simulation and the other part of the network runs in microscopic simulation. The project team performed the analysis for four different operation scenarios based on clustering analysis results. These scenarios were as follows: high demand/high speed/low incidents, high demand/high speed/high incidents, low demand/high speed/low incidents, and high demand/low speed/medium incidents/wet.

Dallas Testbed

This testbed simulated the US–75 Corridor in Dallas, which is 21 mi long. The project team used a mesoscopic simulation-based DTA tool in the simulation. The team selected four operational conditions for modeling based on clustering analysis. The operational conditions were medium-high demand/minor incident, high demand/minor incident, high demand/medium-severity incident, and medium to high demand/high-severity incident.

Pasadena Testbed

The Pasadena City testbed involved mesoscopic simulation-based DTA modeling of a 44.36-mi^2 roadway network, using macroscopic simulation, combined with an 11-mi^2 microscopic model coded in microsimulation (Yelchuru et al. 2017). The project team modeled three operational conditions, including high demand/low to medium incident, medium to high demand/high incident, and high demand/medium incident. The team used a separate simulation using a different simulation tool (TRANSIMS) operating at a mesoscopic level to emulate the use of model-based, real-time predictive engine as part of a decision support system. This tool receives information from virtual detectors in the microscopic simulation transportation network and predicts the operational performance at a mesoscopic level, constituting a two-way interface model. The team used an ATDM selection module integrated in the modeling environment to represent the freeway management decision support system.

San Diego Testbed

The San Diego testbed covered 22 mi of the I–15 freeway facility and associated parallel arterials. The U.S. Department of Transportation (USDOT) also used this testbed for an ICM pilot deployment project. The project team used a microscopic traffic simulation tool. The team identified four operational conditions based on cluster analysis including the following: southbound (a.m.) with medium demand and medium incident, southbound (a.m.) with medium demand and high incident, northbound (p.m.) with medium demand and high incident, and northbound (p.m.) with medium demand and medium incident (Yelchuru et al. 2017).

Chicago Testbed

This testbed covers the Chicago downtown area and the surrounding freeways and arterial networks. The testbed used a mesoscopic simulation-based DTA model, which is a mesoscopic simulation-based DTA tool (Yelchuru et al. 2017). The modeled network included about 4,800 links and 1,500 nodes, with more than 500 signalized intersections. The Chicago testbed simulated six operational conditions and focused on the management of weather-specific events. The modeled conditions included high a.m. demand/high p.m. demand/no incidents, high a.m. demand/high p.m. demand/no incidents/moderate rain a.m./moderate rain to snow, medium a.m. demand/high p.m. demand/no incidents/moderate snow, low a.m. demand/medium p.m. demand/no incidents/moderate snow, medium a.m. demand/high p.m. demand/no incidents/moderate to heavy snow, medium a.m. demand/high p.m. demand/a.m. incidents/moderate snow.

San Mateo Testbed

The network in this testbed covers an 8.5-mi-long stretch of the US 101 freeway and SR 82 located approximately 10 mi south of the San Francisco International Airport. The project team used a microscopic simulation tool for the modeling.

Lessons Learned

This project (Yelchuru et al. 2017) documented several lessons learned, challenges, and gaps based on the modeling activities. The researchers identified a need for additional resources, tools, and techniques to model the wide variety of applications and scenarios using MRM. The scoping of such efforts should also account for the data needs and availability. In the case of using multiple software-in-the-loop emulations of traffic control and management, a central data bus is crucial. The research team also recommended developing an MRM framework to study both ATDM and DMA in an integrated platform. In addition, DMA and ATDM will require additional research to better understand the traveler choice behavior as related to these applications.

The long computation time of the larger and more complex models limited the researcher’s ability to run multiple repetitions of the model with different seed numbers. The long running time will also force modelers to choose between simulating a large variety of operational conditions or simulating more strategies and applications.

In some cases, the researchers faced a lack of the data required for cluster analysis and calibration. The team also had many technical challenges in modeling DMA applications and ATDM strategies because of the unavailability of existing applications and the required increase in the modeling scope. The research team recommended integrating available applications within the next generation of traffic simulation platforms. Another recommendation was the development of a tool that can read vehicle trajectories from simulation and estimate different mobility, safety, and environmental performance measures.

Reported Benefits and Costs

The six testbeds demonstrated the utility of multiresolution simulation in assessing the impacts of a variety of ATDM and DMA applications. In some cases, the testbed setup includes the emulation of a traffic management center (TMC) application, which will help agencies design and refine their TMC decision support systems and operations.

Integrated Corridor Management Analysis, Modeling, and Simulation Experimental Plan

Overview

The USDOT ICM program, starting in 2006, provided the foundation for the ICM deployment efforts in the United States. This program produced guidance to assist agencies in developing and implementing ICM and creating supporting analysis tools, approaches, and technical standards. An important aspect was the use of AMS to support offline and real-time ICM decisions.

FHWA has developed and incorporated a guide for modeling ICM as a volume in the *Traffic Analysis Toolbox Volume XIII* (Alexiadis 2017). This guide recommended the use of MRM for ICM support. According to the framework, the role of each tool type depends on the scope, complexity, and considered questions. Another critical aspect of the ICM AMS methodology is the need for multiscenario simulation that involves simulating transportation systems under several operational conditions. These conditions should represent the expected real-world conditions and cover both recurrent and nonrecurrent traffic congestion (Alexiadis 2017).

Three potential corridor sites (Dallas, San Diego, and Minneapolis, MN) applied the ICM modeling methodology to determine the potential impacts. Later, the project team selected two sites for the actual deployment and used AMS tools for the pre- and post-deployment assessment.

Implementation Descriptions

Assessment of the Impacts of Three Potential Corridors

This project was an early effort of the ICM program to assess the impacts of ICM deployment on the performance of three corridors. The corridors were the US–75 corridor in Dallas, the I-15 corridor in San Diego, and the I–394 corridor in Minneapolis. Alexiadis (2012) reported on this effort, including the analysis methodology, analysis for different operational conditions, performance measures, analysis plans, and estimated benefits.

Dallas As-Planned (Predeployment) Modeling

The project team conducted this effort during the planning and design stage of the ICM pilot project in Dallas (Papayannoulis et al. 2010). In a partial integration, the regional travel demand models provided the network and the demands (O-D matrices) to the mesoscopic simulation model developed using the DIRECT tool. The demand model was also the source for the initial values of modeling parameters, such as the VOT and operating cost per mile, but the project team reviewed and adjusted these values before use. DIRECT allowed the simulation of travelers' selections of route and mode simultaneously. During incidents, the model used an incremental all-or-nothing assignment rather than a DUE assignment to estimate diversion. Cluster analysis results allowed the selection of the operational scenarios for the modeling effort. The assessment of the effectiveness of the ICM strategies was in terms of mobility, reliability, travel time variability, safety, emissions, fuel consumption, costs, toll revenue, and transit ridership. The modeled ICM strategies were multimodal travel time information, incident signal retiming plans, HOT lane with congestion pricing, smart parking system for light-rail transit, light-rail capacity increase, and light-rail station parking expansion.

San Diego, As-Planned (Predeployment) Modeling

The modeling effort in the planning and design stage of the ICM pilot project in San Diego used a microscopic simulation tool (Dhindsa et al. 2010). The regional travel demand model provided inputs to the simulation model. The analyzed ICM strategies were pretrip and en-route traveler information, mode shift to transit, freeway ramp metering, signal coordination on arterials with freeway ramp metering, bus priority, and congestion pricing on managed lanes. The project team obtained the network and the initial trip (O-D) tables from the demand model. However, the team manipulated the demand matrices before using them as inputs to the simulation.

The mode choice of travelers was determined using the mode-choice module in the travel demand model. During incidents or congestion, the models estimated the mode shifts based on en-route information at the microsimulation level. The stochastic user equilibrium-based traffic assignment in the model allowed the estimation of route choice, assuming that travelers did not have perfect information about the network conditions. Further, the model considered peak spreading of demand as a function of the congestion level with different temporal distributions used for each O-D pair.

Dallas As-Deployed (Postdeployment) Modeling

The post-deployment evaluation of the ICM pilot projects in Dallas used AMS tools to assess the impacts of the as-deployed ICM system. The project team also updated the models based on additional data collected from the ICM deployment (Alexiadis 2016a). Specifically, input data modifications included reducing the study area to represent the actual deployment, extending the analysis from the morning (a.m.) peak period to the entire day, adjusting the O-D matrix and network geometry, using multiple signal timing instead of a single plan, and adjusting the percentage of travelers with access to traveler information to reflect the actual use. Some of the above modifications required changes to the DIRECT model. The postdeployment modeling also included postprocessors to calculate travel time reliability, emissions, and fuel consumption based on model outputs. The project team identified 36 operational scenarios based on clustering. The team then analyzed the most impactful clusters representing 10 conditions using the AMS tool.

San Diego As-Deployed (Postdeployment) Modeling

Alexiadis (2016b) discussed the postdeployment effort in San Diego. This effort used a different model from that used in the predeployment modeling, including the use of integrated macroscopic and microscopic simulations modeling. The San Diego Association of Governments Regional Coordinated Travel-Regional Activity Based Modeling Platform travel demand model produced 15-min O-D matrices and the parameters for mode shifts. The static and DTA in a commercially available tool estimated the vehicle routes and performance. The project team calibrated the model for recurrent conditions and an incident day. The team modeled nine representative days/incidents based on the results of clustering analysis. The team also calibrated the model to represent real-world use of express lanes, the access to real-time traveler information, and the percentage of travelers that changed route, mode, and destination. The team also updated the model to calculate travel time reliability, emissions, and fuel consumption based on the California standard.

The project team matched postdeployment traffic and incident conditions to the clusters identified in the predeployment stage. Based on the occurrence of each cluster, the team calculated performance measures and used them to assess impacts of the deployed ICM strategies.

Lessons Learned

A central aspect introduced in the ICM AMS Guide is to consider the impacts of influencing factors and identify the best combinations of scenarios for modeling that represent the actual conditions (Alexiadis 2017). This identification based on cluster analysis allowed modeling that does not under- or overestimate the ICM impacts.

In the San Diego ICM modeling effort, the tools passed trip tables and travel times back and forth at different levels to ensure “stability” between the tools. However, the research team could not guarantee absolute convergence because of other differences between the modeling levels.

The project team reported that, while models may take effort to set up and calibrate, these models can be used one time but for multiple purposes, including assessing the benefits, refining plans and design, and supporting real-time decisions.

Reported Benefits and Costs

Alexiadis (2016a, 2016b) reported that using the AMS approach allowed a detailed analysis of alternatives and a thorough refinement of strategies and plans. The project team also reported that the methodology allowed quantifying potential and actual benefits of ICM. The AMS demonstrated the feasibility of using ICM to reduce congestion. The use of AMS motivated the use of performance measures as a focus of developing and refining the response plans.

For the Dallas and San Diego sites, the costs of the estimated modeling budget were approximately 5 percent of the deployment budget. The partners at the two sites felt that the modeling value greatly outweighed the analysis costs. Alexiadis (2016a, 2016b) reported that the project team expected the costs of modeling in the pilots to be higher than similar future modeling in other regions, since future teams could use best practices from the pilot developments. The demonstration sites also pointed to improved modeling practices, modeling utilization, and data quality control methods because of this effort.

Framework for Multiresolution Analyses of Advanced Traffic Management Strategies

Overview

This project developed a MRM framework for use in the analyses of congestion impacts and traffic management strategies. The framework consists of three components: data from multiple sources and tools that allow the utilization of data to support modeling; supporting environment that assists modelers in developing, calibrating, and processing the results of modeling; and modeling tools of different types and resolution levels that allow the estimation of various performance measures. The project then investigated the ability of the combinations of tools to assess congestion impacts of advanced strategies. As examples, this project applied the MRM framework to the modeling of managed lanes, modeling of work zones, and modeling of active signal control on arterial streets (Hadi et al. 2016).

Implementation Descriptions

Managed Lane Modeling

The modeling of managed lanes in this project took advantage of the data that became available from multiple sources to calibrate and validate the model. In the supply calibration of macroscopic and mesoscopic simulation, roadway capacity and traffic flow models were calibrated based on real-world measures. The demand and road behavior calibration aimed to produce a realistic dynamic O-D matrix and shifts between the express lane and general-purpose lane at short time intervals (e.g., 15 min or 30 min). The researchers tested the impacts of traffic assignment parameters, such as the used VOT, associated stochasticity, and the VOR on producing the demands based on real-world measurements. The study used macroscopic tools—including those in Cube (Bentley Systems 2021), Express Lanes Time of Day (Klodzinski and Adler 2010), and VISUM (PTV Group 2021)—and mesoscopic DTA tools—including Cube Avenue (Bentley Systems 2021) and DTALite (Zhou and Taylor 2014). There was a plan to use a microscopic simulation model developed by the Florida Department of Transportation (FDOT), but the model was not available on time.

Work Zone Modeling

This modeling investigated the ability of different tools to model a work zone with a lane closure. The assessed tools included the analytical tools Q-DAT and QuickZone (Hadi et al. 2016; Curtis and Funderburg 2003), the HCM computational engine work zone module FREEVAL-WZ (Schroeder et al. 2011), the mesoscopic DTA tool DTALite (Zhou and Taylor 2014), and a microscopic simulation tool.

Pattern-Specific Signal Timing Plan Modeling

This study demonstrated the use of a combination of the mesoscopic simulation-based DTA model combined with microscopic simulation to determine the impact of different demand levels during the peak period and the impact of applying pattern-specific signal timing plan on performance.

Lessons Learned

The project reported that the quality of the O-D matrix estimation in all investigated tools greatly depended on the quality of the initial O-D matrix. Some fine-tuning of the matrices produced from the ODME can further improve the results. The project showed that the quality of the ODME improved by using partial O-D matrices and turning movement counts to the estimation process. The core of the managed lane model greatly relied on accurate estimation of the parameters of the VOT, the VOR, and dynamic toll pricing. A sensitivity analysis conducted in this study to examine the impacts of VOT showed that the VOT of $40 produced the best results in terms of predicting the utilization of managed lanes. This value is much higher than the VOT commonly used in the assignment practices in Florida based on a stated preference survey. The project showed the importance of the inclusion of VOR in the assignment. When estimating reliability, the project used a simplified approach to estimate reliability based on equations that take into consideration the impacts of influencing factors on reliability. The research found DTA-based modeling to produce better results than those produced using static-based assignment models in forecasting unseen shifts between general-purpose lanes and managed lanes due to changing toll policies. The use of day-to-day learning in DTALite seemed to be appropriate for long-term work zone modeling.

Reported Benefits and Costs

The results from the case study showed the effectiveness of using DTA tools and multiresolution for managed lanes, work zones, and signal control strategies.

Guidebook on the Utilization of Dynamic Traffic Assignment in Modeling

This document is a volume of the FHWA toolbox and provided guidelines regarding the data needed to run a DTA model, proposed methods for integrating DTA with demand forecasting and microscopic simulation models, and identified methods for integrating DTA within the planning process (Sloboden et al. 2012). The guide discusses the major concepts of DTA, including the use of DUE and “one-shot” non-DUE assignment. It then explains the required and available software capabilities for DTA. The document then presents a modeling framework that provides the overall approach for applying DTA. In addition, the guide discusses the data requirements and methods for developing dynamic O-D matrix inputs. Then, the guide provides information on the development of the base model, including error and model validity checking, the calibration and validation of the model, and alternatives analysis based on the model outputs. A section of approximately two pages provided a brief description of multiresolution and hybrid modeling.

Junction Parameter Calibration for Mesoscopic Simulation in VISSIM

Overview

This paper described the main difference in the modeling of intersections between microscopic and mesoscopic simulation in a commercially available tool (Ehlert et al. 2017). The authors examined the influence of the calibration parameters in the mesoscopic model focusing on the followup, critical gap, and the maximum waiting time for different types of intersections and movements. The study showed that adjusting the three parameters allowed the calibration of the model.

Implementation Descriptions

The researchers examined the impact of fine-tuning the intersection parameters using a single isolated intersection. The researchers varied three calibration parameter values relevant for junction performance with the goal of matching the results as much as possible to those produced by the HCM analysis procedure.

Summary

The calibration exercise demonstrated the ability of the modification of the mesoscopic simulation parameters to replicate HCM parameters. The authors stated that the identified default values in the microscopic simulation tool provide an excellent starting point for calibration. The analyst can then modify these parameters to replicate local conditions. The authors showed that the simulation models are more accurate in modeling conflicting flows because intersection layout and the distribution of traffic flows across lanes are modeled in more detail in the simulation.

FEASIBILITY AND BENEFITS OF MRM

This section reviews studies that examine the effectiveness and benefits of MRM.

An Implementation Framework for Integrating Regional Planning Model with Microscopic Traffic Simulation

Overview

This paper presented an implementation framework for integrating regional planning models with microscopic traffic simulation along with real-world examples. The motivation was that building large-scale microscopic simulation models is costly and requires a significant amount of data, building, and calibration effort, in addition to computational resources. The paper points out that it is not cost-efficient to build simulation models from scratch for individual projects and demonstrated the benefit of the integration in this regard. Integration is also beneficial in maintaining the consistency between planning and operational analysis (Rousseau et al. 2009).

Implementation Descriptions

The paper uses the Atlanta Regional Commission's (ARC) downtown model as an example in its integrated subarea analysis. The ARC modeling projects integrated the regional macroscopic model, the downtown subarea macroscopic model with high network detail and traffic control data, and the microscopic model for the downtown core area in a partial one-directional multimodel resolution.

Lessons Learned

The paper details the challenges and experience of the macro- and microintegration. The authors discuss the additional required data for the microscopic models, preserving network consistency and correspondence (including the node identities) between the different levels, the difference in the goodness-of-fit (calibration requirements) requirements in different modeling levels, and combining the right skill set in the modeling team.

Reported Benefits and Costs

The integrating approach followed by ARC addressed the challenge of maintaining consistency between the individual simulation studies and the regional model in terms of data and assumptions.

Benefits of Linking Macro-Demand Forecasting Models and Microsimulation Models

Overview

This paper examined the benefits and challenges of integrating the operation of these models, realizing the increased use of combinations of demand forecasting models and microscopic simulation models (Holyoak 2009).

Lessons Learned

The paper presented the advantages of macroscopic and microscopic simulations. It also added that linking these two levels of models facilitated harmonious data exchange and improved the operational speed and ability of both model types to forecast traffic conditions. Moreover, using a common data source for both types of modeling helped in obtaining consistent outputs for both application scales. The paper also highlighted that there are practical issues that come with the model integration.

Reported Benefits and Costs

Linking macro- and microlevel models is cost-effective when it comes to developing, applying, and maintaining both model types. It also enables a more effective evaluation of policy measures, adding value to transport-modeling projects. In addition, using a common data source reduces errors in the model interpretation.

Traffic Simulation Performance Optimization through Multiresolution Modeling of Road Segments

Overview

This study proposed a hybrid traffic simulation model that used a high-resolution, agent-based microscopic simulation with a lower-resolution, flow-based macroscopic simulation. An identified problem with using different simulation models in the same run is the fidelity at the boundary between such simulation models. The primary challenge is the aggregation and disaggregation of the vehicles that pass through the boundary. The paper presented a detailed approach to address this issue (Zehe et al. 2015).

Lessons Learned

A hybrid simulation approach to agent-based traffic simulations can result in a great improvement in performance but provides lower model fidelity. However, the study found that when considering macroscopic measures, there is no significant difference between a multiresolution simulation and a pure microscopic approach. When examining microscopic measures, however, the researchers observed a loss in fidelity with the multiresolution approach.

Reported Benefits and Costs

The paper showed that the time required for hybrid simulation can be 20 percent lower than the time required for microscopic simulation while maintaining a relatively high accuracy of below 5 percent deviation from a pure microscopic simulation.

Evaluation of Methods for Calculating Traffic Assignment and Travel Times in Congested Urban Areas with Strategic Transport Models

Overview

This report evaluated methods for traffic assignment modeling (static macroscopic, dynamic macroscopic, and dynamic microscopic and mesoscopic) and found that the meso/microscopic simulation-based DTA model in combination with ABM demand forecasting models are most appropriate for all considered applications in congested urban areas (Flügel et al. 2014).

Implementation Descriptions

The study discussed few possibilities for future developments and implementation of Norwegian demand forecasting models based on the study recommendations.

Lessons Learned

The report mentioned that when integrating a static macroscopic travel demand model with a meso/microscopic simulation-based DTA model, the data structures are not directly compatible. Therefore, methods to disaggregate demands are required when used as inputs to the more detailed model. Before analysts can feed the demands back to the travel demand model, they must aggregate these demands, and information losses will always occur. The proposed integrated ABM and dynamic assignment models require more detailed input data and are more demanding to implement, calibrate, and use. They also require additional expert knowledge. In addition, the stochasticity of the models can be time-consuming, particularly when comparing the performance of improvement alternatives.

Reported Benefits and Costs

The study highlighted the importance of combining dynamic models with ABM for demand forecasting in Norway.

From Macro to Micro—How Much Micro Is Too Much?

Overview

This paper discussed the need for multilevel models, arguing that for each planning task there is an appropriate level of resolution (Wegner 2010).

Implementation Descriptions

The paper presented an example of the multilevel urban model system. The model consists of three spatial levels: region level, zone level, and cell level. The author (Wegner 2010) applied the model in a planning project to forecast long-term economic, social, and environmental impacts. The author stated that the feedback between the three model levels should be both top-down and bottom-up; however, he only implemented the top-down effects.

Summary

The author believes that in a practical aspect, microsimulation models come with limitations and challenges (e.g., high cost, required data, and computational time). Despite recognizing that microscopic simulation allows investigating individual human behavior to better account for increasing diversity and heterogeneity, the author said that analysts should use aggregate models for planning applications in the foreseeable future.

CONSISTENCY OF MULTIRESOLUTION MODELS

This section summarizes studies that addressed consistency and achieving convergence between different levels of multiresolution models.

Modeling for Flexibility and Consistency: An Integration Capability for Mesoscopic Dynamic Traffic Assignment and Microscopic Traffic Simulation Models

Overview

This project examined the integration of mesoscopic and microscopic simulation models providing expanded dimensions of modeling capabilities. To facilitate integration, the project team developed a model conversion tool to combine the mesoscopic simulation abilities of a mesoscopic simulation-based modeling tool with a microscopic simulation tool. The project report addressed the consistency issues encountered during the conversion through a case study that analyzed the outputs of both simulation modeling tools (Shelton 2009; Center for International Intelligent Transportation Research 2010).

Implementation Descriptions

The mesoscopic-to-microscopic model conversion tool is an offline integration tool that automatically converts the mesoscopic subarea to a microscopic equivalent. The project team tested the integration tool through a case study that aimed to analyze the possibility of restricting trucks from the left lane on the freeway.

Lessons Learned

The report addressed a number of consistency issues associated with the conversion process. These issues involve vehicle loading, geometry, time resolution, and traffic dynamics. With regard to vehicle loading, the utilized mesoscopic model generates vehicles directly on “generation links” randomly at the upstream and downstream nodes and at any location between the two nodes. This process is not acceptable for microscopic models, which need to generate the vehicles at fixed points, preferably at local side-street or parking lot access points. One implemented solution was to have a new generation link that represents the generation at fixed points. A second loading issue occurred at the boundary of the subarea if sufficient space did not exist for vehicles to exit at the next ramp or make the next turn at the intersection. The project team also found that microscopic models often produce different results than the macroscopic or mesoscopic models.

Reported Benefits and Costs

The project combines the strengths of both mesoscopic and microscopic simulation models. The new integration tool reduced conversion time while providing much more reliable route representation.

Evaluation and Improvement of Consistency of Hybrid and Multiresolution Traffic Simulation Models

Overview

This paper recognized the need to maintain consistency between the MRM components at two levels: model-based consistency (MBC) and process-based consistency (PBC). MBC is the degree of match between the model outputs and MoEs under various conditions. Analysts need to address MBC consistency as part of the calibration process. PBC refers to maintaining consistency between model results in facility demands as conditions change. Analysts can address this issue through a “feedback iterative process,” in which the information is passed between the different level models to ensure the PBC. The study identified statistical measures to use to evaluate the two types of consistency (Tokishi 2013).

Implementation Descriptions

Using an MRM framework, the study demonstrated a process that can increase MRM network consistency.

Lessons Learned

Based on a review of existing standards and techniques for model calibration, the author used the following statistical measures to examine model consistency:

- Geoffrey E. Havers statistics adjusted for 1 h.
- Percentage of the 5-min periods that meet the acceptable percent or absolute error of link volume.

- Mean percent error of 5-min link speeds.
- Percentage of the 5-min intervals with the error for both speed and flow rate between models equal to 0 at a 95-percent confidence level using a *Z*-test.

MRMs can achieve consistency in both the MBC and PBC contexts. Unsolved errors may still exist even after sensing improvement in evaluation MoEs for MBC and PBC.

Traffic Multiresolution Modeling and Consistency Analysis of Urban Expressway Based on Asynchronous Integration Strategy

Overview

The aim of this paper was to study a multiresolution traffic flow model of an urban expressway, starting with the investigation of the use of three-level MRM. The paper introduced a multiresolution simulation framework and integration strategies (Zhang et al. 2017).

Implementation Descriptions

The study demonstrated using the framework for modeling an expressway in Shanghai, China.

Lessons Learned

The simulation results showed that the volume-density relationships of the three submodels (macro, meso, and micro) agreed with detector data. Interestingly, the study reported that the macromodel had better accuracy than the micro- and mesomodels for the studied network.

Hybrid Traffic Simulation Models: Vehicle Loading at Meso-Micro Boundaries

Overview

This study addressed the loading of vehicles from the mesoscopic model to the microscopic model in a hybrid simulation. The paper presented a new loading method that showed superior performance compared to existing approaches (Burghout 2006). The paper presented a framework for the hybrid meso/micromodels to ensure consistent representation of traffic dynamics and examined the impacts on the consistent representation of the loading of vehicles from the meso- to the micromodel. The paper identified the following consistency issues:

- Consistency in route choice.
- Consistency in network representation.
- Consistency of traffic dynamics, allowing queues to continue through the borders between the modeling components in the hybrid model.
- Consistency in traffic performance.
- Transparency in communication and data exchanges between the models.

Implementation Descriptions

The author performed a case study to highlight the new loading mechanism's significance in improving the accuracy of both hybrid and pure microscopic models.

Lessons Learned

The case study results showed the loading mechanism's importance and the proposed method's benefit. Inappropriate loading methods can produce excessive decelerations and accelerations, difficulty in vehicle entry, reduced capacity at the entry points, and thus unrealistic shockwave propagation.

Reported Benefits and Costs

The proposed method is associated with more realistic accelerations and, consequently, much better modeling. The paper stated that this method is useful for microscopic models on their own, not just hybrid models.

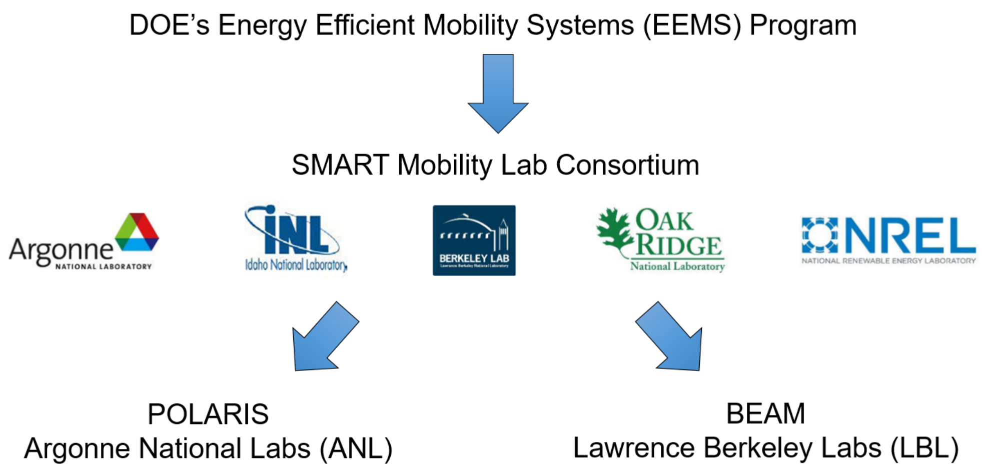
DEVELOPMENTS TO SUPPORT MRM AND HYBRID MODELING

This section reviews developments that support effective and efficient application of MRM and hybrid modeling.

SMART Mobility Lab Platforms

Overview

The U.S. Department of Energy's (DOE's) Energy Efficient Mobility Systems Program has funded the Systems and Modeling for Accelerated Research in Transportation (SMART) Mobility Lab Consortium (U.S. Department of Energy 2020). The Consortium has subsequently developed an entire open-source MRM ecosystem to predict the mobility, energy, and climate change impacts of emerging transportation technologies. Argonne National Laboratory is the lead developer for the Planning and Operations Language for Agent-based Regional Integrated Simulation (POLARIS) software suite (Auld et al. 2016). Lawrence Berkeley Laboratory is the lead developer for the Behavior, Energy, Autonomy, and Mobility (BEAM) software suite (Sheppard et al. 2017). DOE refers to these software suites as modeling workflows. Figure 4 illustrates this research and development initiative.



Source: FHWA.

Figure 4. Flowchart. SMART Mobility Lab platforms.

According to the SMART Mobility capstone report (U.S. Department of Energy 2020), the SMART Mobility researchers recently applied the POLARIS and BEAM platforms to reach the following analysis conclusions:

- Pooled ride-hailing without repositioning decreases VMT.
- Ride-hailing repositioning leads to increased empty miles.
- Driverless vehicles for personal use increase VMT.
- Driverless vehicles for personal use impact travel behavior.
- Transit is critical to mobility.
- Freight movement will be increasingly important to transportation energy use.
- E-commerce increases lowers overall system VMT and energy.
- Shared mobility improves mobility energy productivity (MEP).

Implementation Descriptions

The SMART Mobility Lab software suites (POLARIS and BEAM) have similar attributes. They both offer agent-based, mesoscopic traffic simulation for widearea networks. They both provide microscopic simulation, which is ideal for detailed facility and corridor analysis. Unlike most commercial software suites for MRM, they also offer integration with a vehicle dynamics simulation tool. This tool allows the analyst to observe the impacts of vehicle technology changes on mobility and emissions throughout the traffic network. Table 1 illustrates the similar attributes, and analogous software components, available within both MRM platforms.

Table 1. SMART Mobility Lab platform implementation components (Rousseau 2020).

Platform	Entire Urban Area	Facility/Corridor	Vehicle Dynamics
Attributes	Agent-based, mesoscopic simulation	Microscopic simulation	Vehicle level powertrain simulation

Platform	Entire Urban Area	Facility/Corridor	Vehicle Dynamics
POLARIS	POLARIS	RoadRunner, Aimsun	Autonomie
BEAM	UrbanSim, ADOPT	Aimsun	FastSim

ADOPT = Automotive Deployment Options Projection Tool; Aimsun = Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks.

Lessons Learned

The DOE platforms successfully demonstrate the integration of vehicle dynamics simulation into MRM frameworks. This type of functionality has not been widely advertised by the commercial transportation software vendors. This accomplishment bodes well for future research into changing vehicle and infrastructure technologies.

DOE stakeholders have noted that difficulties in calibration and validation, plus lengthy computer run times, prevent these platforms from being more practical and beneficial (Needell 2020). These same limitations affect all MRM platforms. Increased automation of the calibration and validation process is one candidate solution.

To achieve their goal of assessing MEP, the SMART Mobility researchers implemented a computation using outputs from different tools representing different MRM resolutions (U.S. Department of Energy 2020). Specifically, the SMART Mobility researchers implemented an aggregate computation using outputs from UrbanSim, POLARIS, and Autonomie to better capture the energy, time, and cost of mobility. Therefore, other MRM platforms and analysts could consider implementing calculations that use outputs from different tools representing different MRM resolutions. The MEP inputs used from various models are as follows:

- Study area boundary.
- Travel times by mode.
- Ride-hailing wait times.
- Activity engagement frequencies.
- Operational cost (per passenger mile) by mode.
- Land use (establishments of different acclivity types).
- Population (number of people per block).
- Employment (number of jobs by activity type).
- Energy consumption (per passenger mile) by mode.
- Coefficients for time/cost/energy parameters.

The SMART Mobility researchers used microsimulation to generate fundamental diagrams and then incorporate them into the POLARIS traffic simulator (U.S. Department of Energy 2020). Similarly, researchers used microsimulation to obtain the impact of cooperative adaptive cruise control on highway capacity and then integrated these impacts into BEAM. These examples demonstrate the analysts' desire to pursue and achieve model consistency, feedback, and possibly convergence. They also demonstrate the use of one model's results to help calibrate other models at other resolutions.

Reported Benefits and Costs

The DOE MRM platforms have enabled dozens of research publications (Argonne National Laboratory 2020). Featured examples include "Quantifying the Mobility and Energy Benefits of Automated Mobility Districts Using Microscopic Traffic Simulation" (Zhu et al. 2018), presented at the American Society of Civil Engineers International Conference on Transportation and Development conference held in Pittsburgh, PA, and journal paper "An Optimization-based Planning Tool for On-demand Mobility Service Operations" (Aziz et al. 2019). Key findings include the ability of shared mobility to augment vehicle technology improvement and the specter of ride-hailing causing increased traffic congestion due to empty vehicles (Needell 2020).

Hierarchical Multiresolution Traffic Simulator for Metropolitan Areas: Architecture, Challenges, and Solutions

Overview

This paper presented a hierarchical multiresolution traffic simulation system referred to as METROSIM (Li et al. 2019). METROSIM combines an open-source mesoscopic traffic simulator for regional DTA and a commercial microscopic traffic simulation tool (Li et al. 2019). In this environment, the mesoscopic and microscopic simulation network represent two independent, but highly consistent, networks, and they exchange data while both simulation tools are running. (A related document is *Integrating Meso- and Micro-Simulation Models to Evaluate Traffic Management Strategies* [Mirchandani 2017]).

Implementation Descriptions

The study used a hypothetical case study to demonstrate one of many potential applications of METROSIM.

Lessons Learned

This study presented several solutions to tackle challenges, such as acceptable accuracy, synchronization, parallel computing, and multithreading technology.

Reported Benefits and Costs

In the comparison of METROSIM and conventional methods in signal timing, evaluation showed that, without METROSIM, the benefits of new signal timings in the case study would have been considerably overestimated.

Multi-Model Simulation-Based Optimization applied to Urban Transportation

Overview

This thesis proposed a methodology for the simultaneous use of traffic simulation models with different levels of resolution as part of a simulation-based signal timing optimization (Selvam 2014). The developed framework combines the use of low-efficiency models with high-efficiency models to solve the optimization problem efficiently.

Implementation Descriptions

The researcher applied a simulation-based optimization algorithm to two case studies: a small hypothetical network and a model of Lausanne, Switzerland.

Lessons Learned

At every iteration of the developed model, results from the analytical traffic assignment model allowed the selection between the need for a large-scale or a small-scale simulation model.

Reported Benefits and Costs

The author showed that the proposed algorithm can identify signal plans in a way that reduces the computational cost. The study showed the potential of this method to reduce the overall computation time by 46 percent in the case of simulation-based algorithms. Thus, the proposed framework will be useful for solving large-scale optimization problems using simulation-based optimization.

HyTran: A New Approach for the Combination of Macroscopic and Microscopic Traffic Flow Models

Overview

The objective of this dissertation was to propose a hybrid simulation, referred to as HyTran, which combines a cell transmission model (CTM) and a commercially available microscopic traffic flow simulation model (Huang 2013). The approach allows the models to communicate while simulating different parts of the road network with different modeling levels.

Implementation Descriptions

The researcher used an example of an urban intersection from a real-world road network in Graz, Austria, to compare the performance of two hybrid modeling frameworks: the flow transition-based framework (FTF) and data fusion-based framework (DFF) relative to using the CTM by itself.

Lessons Learned

Both the FTF and DFF improved the performance over that of the CTM model. The study mentioned that analysts should base their selection between FTF and DFF on the specific application. The FTF is more feasible under diverse scenarios in which the microscopic model behavior is too complex to be "projected" into the CTM model. The DFF is more efficient and saves a huge amount of computational resources, and it offers more stable simulation results.

Integrating a Simplified Emission Estimation Model and Mesoscopic Dynamic Traffic Simulator to Efficiently Evaluate Emission Impacts of Traffic Management Strategies

Overview

This paper presents a multiresolution method that postprocesses the results from a mesoscopic simulation-based DTA model at 6-s resolution to generate vehicle trajectories at 0.1-s resolution using a simplified car-following model (Newell's linear car-following model). The study used the results in combination with an emission estimation package to forecast the vehicle emission and fuel consumption impacts of traffic management strategies (Zhou et al. 2015).

Implementation Descriptions

The first test network used was the Fort Worth, TX, subnetwork. The second network was a large-scale triangle network imported from a regional demand model. The study evaluated the impacts of the demand level and the presence of a work zone on travel times and emissions.

Lessons Learned

The study found unrealistic accelerations of the simulated vehicles as some simulated vehicles were changing their speeds from zero to the free-flow speed within 1 s. This problem dealt with prespecified limits of acceleration for each defined speed range. The second identified limitation was the lack of speed variation in the trajectories when the vehicle reached a constant speed.

Reported Benefits and Costs

The utilized open-source framework allows transportation planners to use advanced modeling techniques to evaluate enhancement scenarios with low-computational resources.

A Traffic Simulation Package Based on Travel Demand

Overview

This paper introduced a new traffic simulation package that includes both macroscopic and microscopic simulation (Nguyen 2012). The microscopic model simulates traffic movement with predefined routes of the vehicles and supports the rerouting of vehicles. The macroscopic simulation allows the simulation of larger networks.

Implementation Descriptions

The study area chosen to validate the consistency of the micro and macro simulators was the downtown Melbourne, Australia, area. The researcher performed validation by comparing the densities, speeds, and flow rates between the two modeling components.

Lessons Learned

The study encountered problems during congested conditions in that there were high variances in densities and flows between the two simulators (the microscopic and macroscopic simulation models). This problem seemed to be due to the difference in spillback consideration. The authors said that future work would solve this problem.

The Effective Integration of Analysis, Modeling, and Simulation Tools

Overview

This project developed a prototype data hub and data schema using the Network Explorer for Traffic Analysis (NeXTA) open-source software tool (Nevers et al. 2013). The objective was to save users time when inputting data and to model and display results in a common format. The researchers demonstrated this application at Portland, OR, Metro and Pima, AZ, Association of Governments. The applications were successful in taking existing regional travel demand models and exporting the data to a mesoscopic simulation-based DTA tool, exporting to a signal timing optimization tool, and then exporting to a microscopic simulation tool for detailed operations analysis.

Implementation Descriptions

The test application to demonstrate the use of the AMS data hub through NeXTA involved multiresolution analyses in Portland and Tucson, AZ. In Portland, Northwest 185th Avenue bisects two communities (Beaverton and Hillsboro) of rapidly rising population, but regional livability policy restricts the amount of roadway widening that can occur. Therefore, the research team endeavored to demonstrate the benefits of MRM over traditional approaches in identifying the time-dependent impacts on routing and demand and evaluating ITS treatments along the corridor (e.g., ramp metering strategies, adaptive signal control, transit priority, truck priority).

In Tucson, the Casa Grande Highway is an important corridor serving commuters as well as interstate traffic. The State DOT and FHWA have identified the need to increase roadway capacity and improve operational efficiency. Therefore, the research team sought to demonstrate the benefits of MRM over traditional approaches in identifying future capacity requirements for the corridor, and in evaluating optimal construction sequencing for the corridor.

Reported Benefits and Costs

The analyses took only 7–11 h to complete using the data hub compared to 35-52 h without the data hub, translating to a total time savings of 80 percent.

Data Consistency of Multiresolution Traffic Simulation Systems

Overview

This study designed an architecture of a Hybrid Traffic Simulation System and presented three ways to resolve the consistencies of data and logic: data structure design, architecture design, and controller design (Ma et al. 2013).

Implementation Descriptions

A case study demonstrated the architecture and structure.

A Study on Multi-Resolution Modeling of Mesoscopic-Microscopic Traffic Simulation Model

Overview

This paper introduced an MRM approach that combined a mesoscopic and microscopic model. The study showed that the hybrid scheme can keep the results consistent between the two model levels (Zhang 2012).

Implementation Descriptions

The study developed a framework based on data flow, user interface layer, data fusion layer, logical processing layer, and data analysis layer.

Lessons Learned

The mesoscopic model can achieve a higher running efficiency and relatively low precision for a large-scale network. However, for the small-scale network, the micro-model can obtain a higher precision and relatively low running efficiency. The paper compared compression wave and vehicle trajectory data between the two models and showed consistent results.

Reported Benefits and Costs

The study implemented the hybrid scheme of both simulation models, and the results showed that the hybrid scheme can keep the results consistent between the mesoscopic model and the Wiedemann model.

APPLICATIONS OF MULTIRESOLUTION AND HYBRID MODELING

This section includes a review of the applications of MRM in real-world projects or in demonstrating the effectiveness of MRM to model specific applications.

Impacts of Connected Vehicles in a Complex, Congested Urban Freeway Setting Using Multi-Resolution Modeling Methods

Overview

In this paper, the researchers used macroscopic, mesoscopic, and microscopic models to determine the effect of connected vehicles (CVs) on traffic flow (Shelton et al. 2019). The researchers first simulated CVs on a small network using microscopic simulation based on previously reported approaches in the literature. The research team then assessed the effects of CV technology on congestion and mobility using DTA modeling.

Implementation Descriptions

The research team modeled a 12-mi stretch of I–35 near Austin, TX, due to its well-known congestion issues. The researchers derived traffic volume demands from population estimates from 2035. Frontage roads were not included in the model. Desired headways for CVs and nonequipped vehicles were 0.55 s and 0.90 s, respectively. The desired speed for CVs was 68 mph. For nonequipped vehicles, the desired speed had a distribution between 58 and 72 mph.

Reported Benefits and Costs

In this study, the main benefit of MRM was the ability to generate a calibrated baseline microsimulation model (without CVs) of I–35, which was consistent with Austin, TX-area regional DTA models. The analysts had more confidence in their baseline model than they would have without MRM. However, the researchers apparently did not analyze CVs at the meso or macro levels.

The Research of Multi-Resolution Modeling and Simulation of the Emergency Evacuation

Overview

This paper presented the use of two resolutions of simulation for pedestrian evacuation. The first involved a multiagent framework and a modified particle swarm optimization (PSO) algorithm. The second used the Euler equations of fluid dynamics. The study used an aggregate/disaggregate algorithm for the model interaction and parallel computing of the model levels (Yang 2012).

Implementation Descriptions

These frameworks modeled pedestrians independently at the micro level. They modeled pedestrians via fluid dynamics at the macro level. They modeled human decisions in an agent-based manner. They used PSO to optimize people’s behaviors at the micro level.

Lessons Learned

The researchers simulated five evacuation exits at Optical Valley Plaza in Wuhan City, China. Based on the simulation results, the researchers were able to recommend infrastructure improvements associated with certain exits and visual guidance to encourage pedestrians to use different exits.

Reported Benefits and Costs

The researchers believe both the macro (fluid-based) and micro (agent-based) theories are valid and useful. They hope to obtain more evidence of this hypothesis with future research.

Twin Cities Metro-Wide Traffic Micro-Simulation Feasibility Investigation

Overview

This project evaluated the feasibility and approaches for developing traffic simulation models for the Minneapolis-St. Paul metropolitan area, taking into consideration local needs and capabilities (Michalopoulos 2008). The research team determined that the most appropriate approach was to use a hybrid mesoscopic/microscopic simulation application with close integration with a macroscopic planning model.

Implementation Descriptions

The feasibility investigation consisted of a state-of-practice review for wide-area simulation, identifying Twin Cities' stakeholder needs, a data needs assessment, and a level-of-effort forecast for operations and maintenance of models.

Lessons Learned

The research team concluded that commercial tools were preferable to ensure quality technical support and continuous tool improvements. Although the team would have preferred a purely micro solution, data availability was insufficient to support this option.

Reported Benefits and Costs

The research team did not consider computer run times too high for microsimulation, even for large models. However, data requirements and calibration requirements make microsimulation impractical for large networks. The authors believe an example from Barceló et al. (2006) clearly demonstrated the benefits of hybrid meso/micro simulation.

Examination of Traffic Incident Management Strategies via Multiresolution Modeling with Dynamic Traffic Assignment

Overview

This MRM application used a mesoscopic simulation-based DTA to estimate the impacts of traffic incident management (TIM) considering diversion (Luo and Joshua 2012). The researchers obtained initial vehicle origins, destinations, and volumes from the demand forecasting model. The researchers used a mesoscopic simulation-based DTA model to obtain volumes, vehicle paths, and resulting travel times. The researchers imported output from the mesoscopic model into a microsimulation model for more detailed analysis.

Implementation Descriptions

The researchers said, despite the MRM capability, analysts can conduct most of the TIM analysis at the mesoscopic level. The researchers used a case study in which the incident lasted 3 h and 20 min, and detailed data were available regarding the traffic impacts of this crash. The researchers analyzed four scenarios (i.e., no crash, no TIM after the crash, dynamic message signs and ramp metering after the crash, dynamic message signs and ramp metering and coordinated timings on nearby arterials after the crash). They focused their analysis on a subarea representing approximately one-third of the region. They used probe data to help calibrate the models.

Lessons Learned

The researchers' hypothesis was that a mesoscopic simulation-based DTA could overcome the natural limitations of both travel demand models and microsimulation models for TIM applications. A graph of travel time by time of day showed that the TIM strategies provided substantial and dramatic delay reductions.

Reported Benefits and Costs

The researchers said simulation tools could simulate each of their four scenarios within only 10 min. They completed the study effort within only 16 mo using in-house staff.

Determining Road User Costs for Work Zone Construction Sequencing Using Multi-Resolution Modeling Methods

Overview

This study used MRM to estimate the user costs and systemwide impacts of traffic diversion due to work zones. The research team used a simulation-based mesoscopic model to determine the diversion of vehicles based on the work zone construction schedule. Then the team extracted a subarea and converted it to a microscopic model to better estimate the performance. The team then used a deterministic model to calculate the road user cost due to construction (Shelton et al. 2012).

Implementation Descriptions

The research team developed a deterministic road user cost model, which would use the microscopic and mesoscopic simulation performance measures as inputs. The team used a case study in El Paso, TX, to test the proposed methodology. The proposed cost model accounted for inflation rates, maintenance costs, fuel costs, work zone durations, congestion-induced delays, and traffic volume demands.

Reported Benefits and Costs

Despite many available methods in the literature for estimating road user costs, the research team believed MRM would be highly effective at capturing the precise impacts of route shifting caused by work zones. Because work zones are so common for roadway maintenance and construction, State agencies are keenly interested in knowing the systemwide benefits and costs of these diversions.

Some of the costs for simulation users include those associated with fuel, construction, inflation, tires, repair, depreciation, and State-specific user costs. However, analysts may also need these costs to estimate road-user costs without MRM.

FINDINGS FROM THE REVIEW OF LITERATURE

The review of literature indicates that MRM is most valuable for changes that cause regional impacts on the behaviors of travelers. In particular, such models are sensitive to policy variables such as pricing strategies (fixed or dynamic), vehicle eligibility to use lanes, and lane access control. These models are also powerful in assessing the impacts of temporary capacity disruptions and TSMO projects, including dynamic lane control, ramp metering, and incident management. Other potential applications include the effects of new land uses, analysis of BRT corridors, and analysis of road diets. In addition, these models produce a more comprehensive range of useful performance measure statistics that are not available from the traditional models to support the agency's decisions. However, the literature has stated that, in some cases, for full-impact assessment, analysts will need to model additional strategic behaviors, such as model shift and time shift, in addition to route choice.

For large-scale implementations, particularly when there was feedback from the mesoscopic model to the ABM demand forecasting model, the literature revealed difficulties and time constraints that limited the validation of the model. In addition, the reviewed literature indicates that the availability of the required data varies by region, which was an identified difficulty with the modeling effort. In addition, the run times of these models can be excessive for large networks. The long computation time of the larger and more complex models limited the researchers' ability to run multiple repetitions of the model with different seed numbers. The long running time also forced modelers to choose between simulating a large variety of operational conditions or simulating more strategies and applications. Teams that worked on large-scale MRM projects reported a long time required to edit and debug the network extracted from the demand models due to the low quality of the coding for many of these models. Such coding may be sufficient for the static demand models but not for the higher-resolution models.

Analysts must collect and input additional information into the more detailed models. This input requires a significant manual effort. Recommendations to address this issue were to use multiresolution networks, use default signal phasing/timings for locations outside the area of conflict, and create a link between signal optimization tool files and the DTA models. However, it was argued that, while the MRM models may take effort to set up and calibrate, these models can be used for multiple purposes, including assessing the benefits, refining plans and design, real-time decision support, and more.

Another major issue with which the projects had to deal was the loading of the network when the more detailed traffic simulation was used. These models require realistic zone representations and zone connections to the network.

There were also challenges with dynamic transit assignment. The assessment conducted as part of the SHRP 2 Implementation Program indicates that the dynamic transit assignment model and its integration into MRM has a low level of maturity. Several issues make dynamic transit passenger assignment difficult.

The reviewed studies have also reported on the importance of high-quality O-D matrices, which can be a challenge. The use of partial O-D matrices from third-party vendors should increase the quality of the prediction. There were attempts to use reliability as well as travel time in the traffic assignment, and the literature showed this could possibly improve the results. When modeling managed lanes and the impacts of pricing, the dollar values of travel time and travel time reliability will have significant impacts on the results.

The modeling of DMA and ATDM requires additional research to better understand the shift in traveler choice behavior, as related to these applications. In addition, to better model the impacts of these strategies, the literature recommended cluster analysis for multi-scenario modeling, particularly of DMA and ATDM applications. However, in some cases, there is a lack of sufficient data for cluster analysis. The researchers also had many technical challenges in modeling DMA applications and ATDM strategies because of the unavailability of existing applications to inform the modeling and calibration. There was a recommendation for integrating available DMA and ATDM applications within the next generation of traffic simulation platforms. There was also a recommendation for the development of a tool that would read vehicle trajectories from simulation and estimate different mobility, safety, and environmental performance measures.

A critical issue is the integrated model convergence and the need to identify equilibration convergence strategies and prerequisites to ensure effective alternative analysis. The lack of convergence will reduce the reliability of the evaluation of the alternatives based on the modeling results. In addition, researchers found that using congested travel times from DTA as part of the ABM-DTA may lead to schedule inconsistency between ABM travel times and what results from the DTA. The researchers suggested methods to mitigate this issue.

There has been limited research on the consistency of the different resolutions. For example, in the San Diego ICM modeling effort, the tools passed trip tables and travel times back and forth between different levels to ensure stability between these tools. However, the research team mentioned that absolute convergence was not always possible because of fundamental differences between the modeling levels.

Past work emphasized the importance of preserving network consistency and correspondence (including the node identities) between the different levels of MRM. In previous studies, researchers analyzed the consistency of vehicle loading, geometry, time resolution, and traffic dynamics. They argued that analysts should consider both the MBC and PBC. The MBC is the degree of match between the model outputs and MoEs under various conditions. The PBC refers to maintaining consistency between model results in facility demands as conditions change. Based on a review of existing standards and techniques for model calibration, researchers have proposed statistical measures to examine model consistency. However, unsolved errors may still exist even after an attempt to reach model consistency due to the differences in the details and resolutions of the models. An issue affecting consistency is the difference in the goodness of fit (calibration) required in different modeling levels.

An identified problem with hybrid simulation that involves using different simulation models in the same run is the fidelity at the boundary between such simulation models. Aggregation and disaggregation of vehicles passing through the boundary cause discrepancies. A number of studies have provided approaches to mitigate this problem.

CHAPTER 6. QUALITATIVE DATA ANALYSIS

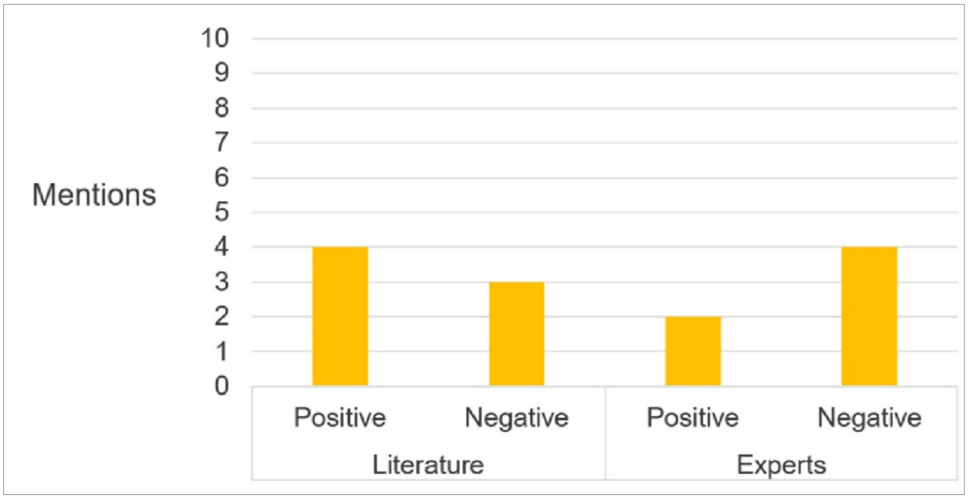
Chapter 4 (Summary of Outreach) and Chapter 5 (Literature Review) allude to a significant amount of text-based responses and content collected by the MRM research team. A qualitative data analysis can help to transform text-based responses and content into quantifiable information (Medelyan 2020). The team performed an analysis of the outreach teleconference transcripts and literature review. For this analysis, the team did not include the gap analysis transcripts. Instead, the team only included the state-of-practice teleconference transcripts.

The team focused on the following key MRM topics for the qualitative data analysis:

- Run times.
- Edge models.
- Hybrid models.
- Reused models.
- Activity-based models.
- Success stories or pilots.
- Consistency and feedback.
- Microsimulation for large networks.

RUN TIMES (13 MENTIONS)

Computer run times for MRM are a significant expense to the analyst and the agency. These run times may be on the order of several hours or several days for a single scenario evaluation. Figure 5 conveys some of the mixed messages encountered by the research team. Although run times are a definite source of hesitation for prospective users, some experienced modelers believe it is important to stick with MRM, because improving computer speeds will gradually mitigate this obstacle.

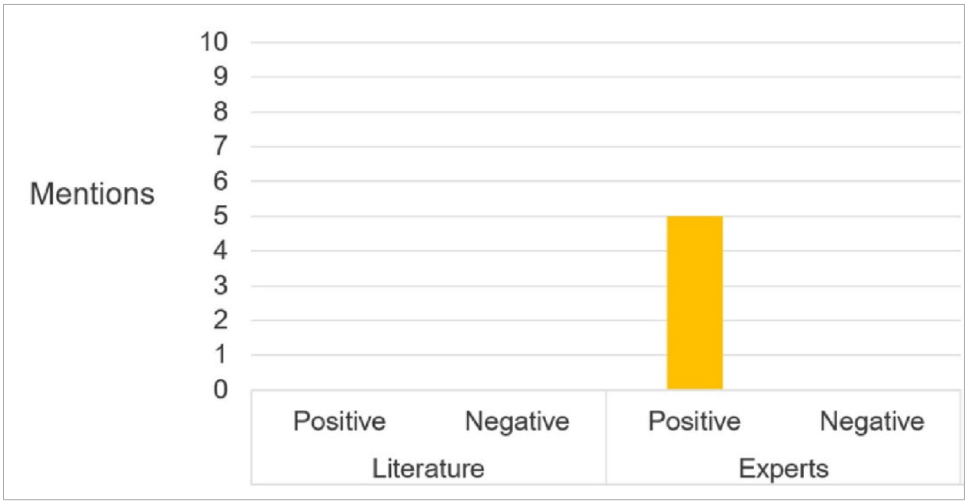


Source: FHWA.

Figure 5. Bar Chart. Qualitative discussion of run times.

EDGE MODELS (FIVE MENTIONS)

During the discussions with MRM experts, the research team noted that some practitioners were deliberately creating models with much more detail and accuracy than are typically associated with a given modeling resolution. In other words, a modeler would sometimes convert a coarse model to a more detailed model prior to exporting data to the lower resolution(s). Because these models seem to sit on the edge between macroscopic and mesoscopic, or mesoscopic and microscopic resolutions, the research team coined the term "edge models" to describe these models, although there is no known technical term as such. Figure 6 implies that practice may be ahead of research in uncovering the utility of this approach.

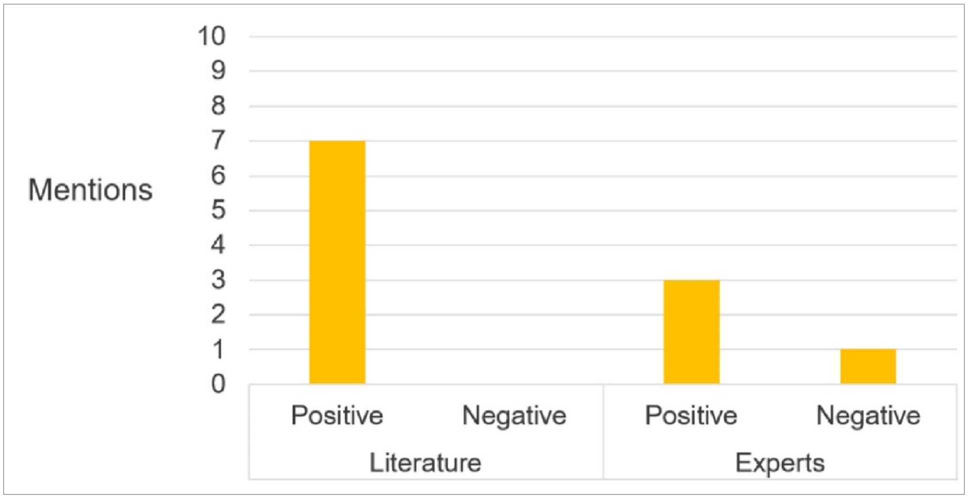


Source: FHWA.

Figure 6. Bar Chart. Qualitative discussion of edge models.

HYBRID MODELS (11 MENTIONS)

Chapter 2 (Terminology and Definitions) defined hybrid models as simulations that use two different modeling resolutions concurrently, with real-time network information exchanges (Banister 1995). The state-of-practice outreach found that analysts may choose to model key areas of the network in higher resolutions. Although two of the vendors said that there is currently little commercial interest in hybrid modeling, one practitioner planned to explore hybrid options more in the future as a possible cost-effective solution for wide-area models involving microsimulation. The larger number of mentions on the literature side versus the outreach side (figure 7) indicates that academia may be ahead of practice in this area, or it may indicate that the commercial tools for hybrid modeling are not yet efficient enough to make the approach cost-effective.

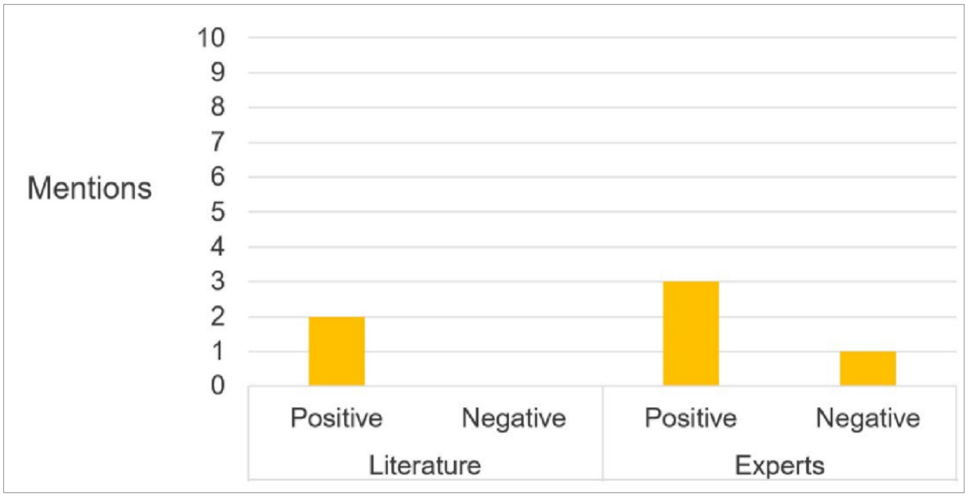


Source: FHWA.

Figure 7. Bar Chart. Qualitative discussion of hybrid models.

REUSE OF MODELS (SIX MENTIONS)

A few practitioners and researchers expressed enthusiasm about the ability to reuse traffic network databases as a major benefit of MRM. For example, a regional MRM database could help to export dozens of subarea microsimulation models over a 5- to-10-yr period. However, one practitioner noted that, in some cases, the money saved on reduced data entry could be somewhat canceled out by increased model calibration costs. Since reuse of models is not a highly technical or theoretical topic, it is unsurprising that figure 8 shows more mentions from practitioner responses than from the literature review.

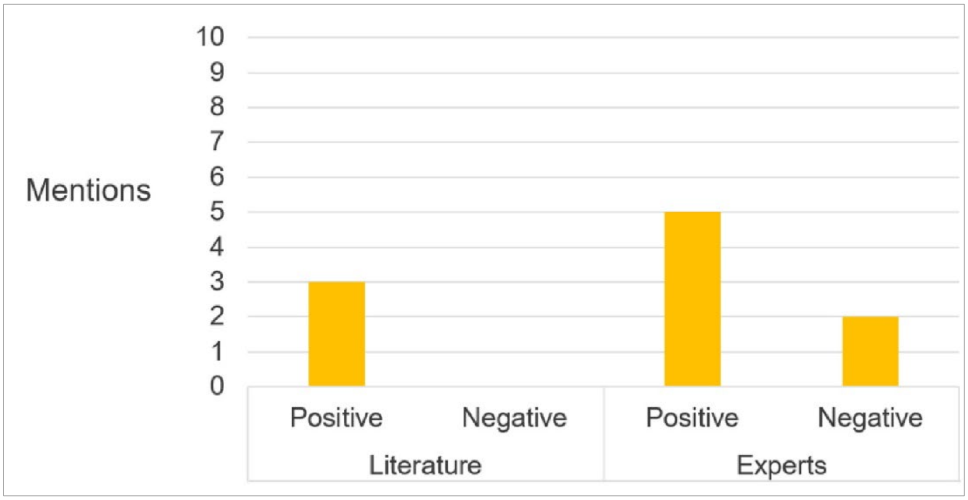


Source: FHWA.

Figure 8. Bar Chart. Qualitative discussion of re-use of models.

ABM (10 MENTIONS)

During the outreach discussions, practitioners seemed excited about the modeling efficiency and capability provided by ABM. As shown in figure 9, ABM may be another example of practice advancing ahead of research in certain areas. The research team noticed that practitioners were increasingly using ABM as a substitute for the traditional four-step planning models. One of the software vendors also said that ABM is able to "sidestep" the MRM "problem" for large-scale simulation, presumably in terms of modeling efficiency.



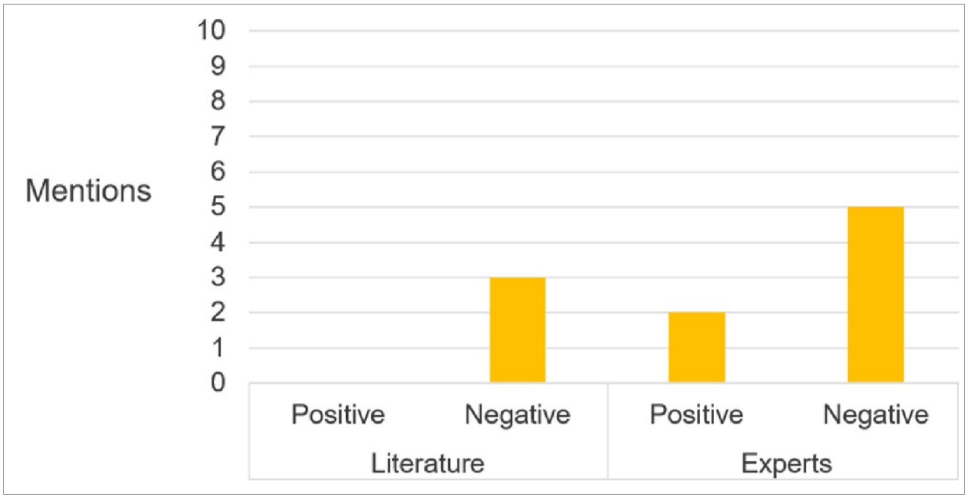
Source: FHWA.

Figure 9. Bar Chart. Qualitative discussion of activity-based models.

MICROSIMULATION FOR LARGE NETWORKS (10 MENTIONS)

Perhaps in part due to the complexities and challenges associated with MRM, some practitioners and vendors view microsimulation of large networks as an inevitable solution. Indeed, if computer speeds were much faster and calibration processes involved much more automation, microsimulation of large networks would become more practical. There would be less of a need to apply multiple modeling tools or resolutions.

Based on the information collected by the MRM research team (figure 10), most practitioners and researchers continue to view microsimulation of large networks in a negative light. This view was mainly due to excessive data entry requirements, computer run times, and calibration efforts. One vendor even mentioned that a major push for microsimulation of large networks failed approximately 10 yr ago, and that no one has yet been motivated to pursue a similar effort.

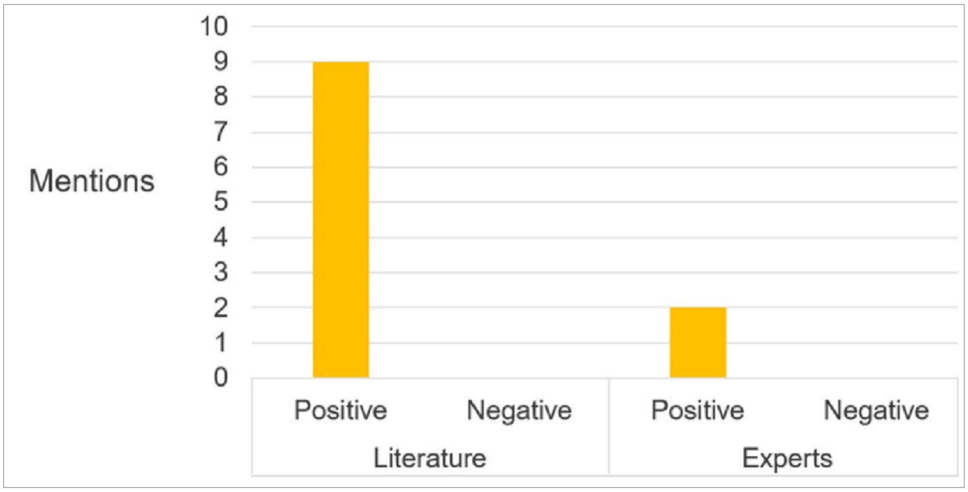


Source: FHWA.

Figure 10. Bar Chart. Qualitative discussion of microsimulation for large networks.

SUCCESS STORIES OR PILOTS (11 MENTIONS)

Figure 11 corroborates a sentiment heard by the research team, which is that success stories and pilot projects would be helpful in accelerating the adoption of MRM, as has already occurred in certain States. Unsurprisingly, many research papers and reports in the literature described successful implementations of MRM. However, the small number of success stories and pilot projects reported by practitioners likely indicates that their projects did not specifically intend to illustrate the benefits of MRM, and the practitioners probably did not perform or document any comparisons to single-resolution modeling.

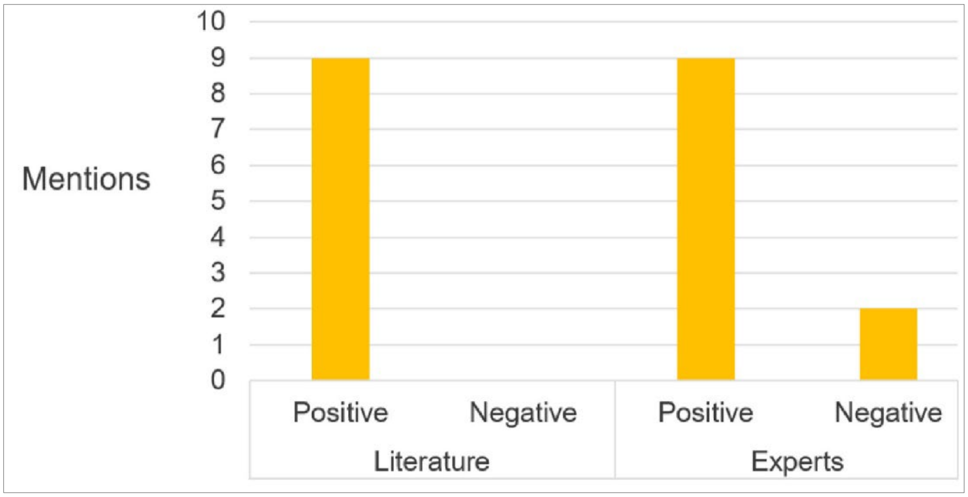


Source: FHWA.

Figure 11. Bar Chart. Qualitative discussion of success stories or pilots.

CONSISTENCY AND FEEDBACK (20 MENTIONS)

Figure 12 illustrates the large number of mentions for this key MRM topic area. A strong majority of practitioners and researchers viewed consistency and feedback between the modeling resolutions as a key MRM goal. However, although everyone seems to aspire to this goal, the research team believes that even the MRM experts are merely scratching the surface of this concept. Their understanding of the concept is limited. Commercial vendors have not provided much automation to facilitate such analyses. Regarding the small number of negative responses shown in figure 12, these MRM experts did not view the pursuit of consistency and feedback as particularly helpful or cost-effective.



Source: FHWA.

Figure 12. Bar Chart. Qualitative discussion of consistency and feedback.

SUMMARY

In many cases and topics, this chapter's qualitative data analysis merely confirmed prior perceptions held by the MRM research team. However, the team viewed the short list of findings below as interesting, which may not have been noticed without the qualitative analysis:

- Practitioners are innovating more than researchers with regard to the edge models.
- Reuse of MRM models may save money on data entry but may cause analysts to spend more money on calibration.
- Integration of ABM and DTA has been quite successful; this integration may evolve into an important and attractive capability within the MRM process.

CHAPTER 7. SUMMARY OF GAP ANALYSIS OUTREACH

The gap analysis in chapter 8 of this report largely reflects the collected information from 14 conversations conducted as part of the state-of-practice review and the additional 5 conversations conducted in the gap analysis. Chapter 4 summarizes the 14 conversations and the associated findings. This chapter summarizes the findings from the five teleconferences as part of the gap analysis task.

The conversations conducted as part of the gap analysis task sought to explore the reasons behind agencies' hesitation to adopt MRM. The team obtained feedback from five departments of transportation (DOT):

- Arkansas DOT (ARDOT).
- Wisconsin DOT (WisDOT).
- Washington State DOT (WSDOT).
- Virginia DOT (VDOT) (via their consultants).
- Maryland DOT State Highway Administration (MDOT SHA).

Table 2 shows a list of the 19 agencies contacted as part of the state-of-practice review and gap analysis.

Table 2. Outreach agencies.

Task	Agency Name	Agency Category
State of the practice	San Francisco County Transportation Authority	County
	FDOT Central Office	State
	Vendor 1	Vendor, consultant
	Nevada DOT (NDOT)	State
	Vendor 2	Vendor
	Texas DOT	State
	ARC	MPO
	Vendor 3	Vendor
	University of California at Irvine	Academic
	FDOT	State
	Vendor 4	Vendor
	Maricopa Association of Governments	MPO
	Consultant 1	Consultant
	Consultant 2	Consultant
Gap analysis	ARDOT	State
	VDOT	State
	WisDOT	State
	WSDOT	State
	MDOT SHA	State

MPO = metropolitan planning organization.

FINDINGS FROM THE GAP ANALYSIS OUTREACH

The remainder of this chapter summarizes the findings from the five conversations in the gap analysis tasks. The gap analysis discussion in chapter 8 references the findings from all 19 conversations.

Start-Up Costs

State agencies recognize that the DOT must immediately pay many MRM costs out of DOT funds. These costs may include staff training, data collection, data entry, and software license fees. Because of these costs, DOTs are motivated to establish positive benefit-cost ratios prior to pursuing an MRM project. This uncertainty about benefits may diminish the ability to establish positive benefit-cost ratios.

Learning Curves

State agencies recognize that they may need a critical mass of MRM projects for their staff to become proficient in MRM tools and methods. Moreover, at State wages, many of the traffic modeling experts ultimately defect to the private sector or to urban areas.

Insufficient Guidance

Although many States have developed internal guidance documents on traffic modeling, little such guidance exists for MRM (Institute of Transportation Engineers 2020). Moreover, little MRM information exists at the Federal level; although *Traffic Analysis Toolbox Volume XIV* devotes several pages to discussing MRM at a high level to support the assertion that DTA is an essential element of the MRM framework (Sloboden et al. 2012).

Tools Not Well Integrated

Some of the modeling experts have pointed out that the integration of traffic analysis tools between different resolutions, such as meso, macro, and micro, is not as seamless as it could or should be. This lack of seamlessness sometimes leads agencies to develop proprietary, homemade solutions and not share them with other agencies or consultants.

Functions Not Well Automated

Many popular commercial tools do not prioritize MRM, and thus they may not provide key data processing functions such as the National Cooperative Highway Research Program (NCHRP) 765 procedure (Horowitz et al. 2014). The lack of these functions again may lead agencies to develop proprietary, homemade solutions and not share them with other agencies or consultants.

Few Success Stories or Pilot Projects

The team heard from some modeling experts that their State would need success stories and pilot projects to make MRM more accepted. For example, during the team's outreach discussions, a professor said that the California DOT subsequently used one of its university's MRM projects from 2007 as a template and blueprint for dozens of follow-on projects.[1] But not all pilot projects share the same qualities and characteristics. For example, ARDOT expressed interest in subarea analysis involving DTA, whereas other States may have interest in larger regional models[2].

Uncertainty about Cost-Effectiveness

WisDOT feedback was notable for its assertion that modelers must essentially prove their analyses to be cost-effective before they begin[3]. They further recommended that someone develop a high-level cost-estimation procedure as a function of several parametric values (e.g., zones, lane miles, periods, scenarios). It appears that units responsible for program delivery may be averse to implementing solutions with unknown technology readiness and maturity.

Current Analyses Not Being Challenged

The final two reasons for MRM not being adopted may fall into the category of lack of incentive to use MRM, rather than barrier to using MRM. Some State representatives noted that clients or stakeholders in their State, despite not having the typical backup and justification that MRM provides, generally do not challenge their current traffic analyses. However, the willingness to challenge current analyses may depend on the agency conducting the project and the type of project.

Little Need for Large Spatiotemporal Scopes

Some agencies realize that MRM pays significant dividends when subsystems interact and when regions are highly congested. However, for regions or roadways that experience minimal congestion, MRM approaches may not be cost-effective.

SUMMARY

In addition to the 14 teleconferences conducted as part of the state-of-the-practice review, the project team conducted 5 more teleconferences with additional agencies that have limited experience with MRM to have a more general assessment. Some of the issues and concerns of the agencies highlighted in the five interviews include the start-up costs, learning curve requirement, insufficient guidance, tools not well integrated, functions not well automated, few success stories or pilot projects, uncertainty about cost-effectiveness, current analyses using traditional methods not being challenged, and, depending on the specific agency and project, little need for large spatiotemporal scopes.

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[1] Jayakrishnan, R. (University of California at Irvine); phone interview conducted by Mohammed Hadi, Xuesong (Simon) Zhou, and David Hale (research team) in the spring of 2020.

[2] Warren, Andrew (ARDOT); phone interview conducted by Mohammed Hadi, Xuesong (Simon) Zhou, and David Hale (research team) in the spring of 2020.

[3] Haskell, Vicki, and Benjamin Rouleau (WisDOT); phone interview conducted by Mohammed Hadi, Xuesong (Simon) Zhou, and David Hale (research team) in the spring of 2020.

CHAPTER 8. GAP ANALYSIS

As discussed in chapter 4 and chapter 5, the reviewed literature and discussions with public agencies and consultants indicate an increasing interest in the use of MRM. Applications of MRM have been limited, despite the identified interest. In addition, the review identified limitations of the existing MRM applications that can reduce the effectiveness of the modeling. Thus, there is a need to assess the hurdles to widespread adoption of MRM by public agencies and the constraints and limitations that reduce the effectiveness of MRM.

The gap analysis presented in this chapter reflects the collected information and findings from the 14 conversations held with the users and vendors of multiresolution tools summarized in chapter 4 and the review of literature summarized in chapter 5. The state-of-practice review teleconferences focused on agencies with extensive MRM experience. To have a more general assessment, the project team, as part of the gap assessment task, conducted five more teleconferences with additional agencies that had limited experience with MRM. The teleconferences included a new set of questions directly related to the gap analyses.

The review of literature and the outreach conducted in this study indicate that some of the constraints and limitations are associated with the available methodologies, guidance, procedures, data, and tools available to transportation agencies. However, there are other issues related to policies, staffing, training, collaboration and information sharing, and attitudes toward simulation modeling that can significantly impact the adoption and effectiveness of MRM. Given the several dimensions and subdimensions of the gaps associated with the MRM, the project team used the same dimensions used in the capability maturity model (CMM) framework (Federal Highway Administration 2012) in the gap analysis. A SHRP 2 reliability program project (Parsons Brinckerhoff et al. 2012) originally developed the CMM for agency self-assessment of TSMO capabilities.

This project categorizes the identified MRM gaps in the six dimensions of the CMM framework. The gaps categorized by the six CMM dimension are as follows, with details discussed later in this chapter:

- Business processes: These processes include the need for the institutionalization of the use of MRM for certain types of analysis; development, provision of methodology, and guidance; allocation of funding and project time to meet the requirements for MRM; the adoption of processes for model archiving and maintenance; and the enhancement of contracting and procurement practices.

- Performance measurements: Performance measurements and estimation are important for model calibration and alternative analysis based on the modeling results. Several gaps in the performance measurement dimension include variations in the definitions and methods used in the estimation of various performance metrics, data needs, plus the types and resolutions of measures used in model calibration and validation.

- Systems and technology: The gaps in this dimension include the need for the development and/or enhancements of methods and tools that support the integration and data conversion between different modeling levels, MRM, multimodal modeling, modeling of emerging technologies challenges, assessment of various levels of behavioral responses to advanced technologies and strategies, simulation/model coupling for real-time management applications, and feedback loop in internally consistent cross-resolution traffic representation.

- Organization and workforce: The gaps in this dimension involve the need for qualified staff to develop, calibrate, and peer review the developed models. There is a need to acquire the experience and background through the recruitment, retention, and training of staff to support the MRM effort.

- Collaboration: Collaboration is an important dimension to support successful MRM. The collaboration can include interagency and intra-agency collaboration that includes the collaboration within the agency as well as collaboration and information sharing with public and private agencies in the region, State, and the Nation.

- Culture: MRM users can define culture as the degree to which MRM implementation benefits are valued by the transportation agency. As described later in this document, there is a variation in the levels of adoption and interest of agencies in MRM.

This chapter includes the analysis of the gaps facing the adoption and effective utilization of MRM. The analysis categorizes the gaps according to the six capability dimensions, which are the business processes, performance measurement, system and technologies, organization and workforce, collaboration, and culture. The analysis reflects the collected information and findings from the conversations and review of literature conducted as part of the state-of-practice review and the conversations conducted as part of the gap analysis of this project.

BUSINESS PROCESSES

Business processes refer to activities such as planning, programming, agency project development processes, and those organizational aspects that govern various technical or administrative functions such as training, human resource management, contracting and procurement, information technology, or coordination. In many cases, the business process elements go beyond the day-to-day operational activities and require broader institutional support and involvement to address (Federal Highway Administration 2020).

Institutionalization and Provision of Guidance

Several state agencies reported in the conversations that they need to formalize and institutionalize MRM utilization in order for MRM to be widely used by the modeling community. These State agencies have existing processes to use analysis tools and methods, but these processes do not include the use of MRM. The formalized process can indicate when such modeling is beneficial and when it has the potential to produce more accurate results than the current practices.

There is also a potential benefit for the development and adoption of procedures and guidance for MRM utilization[1,2]. Currently, most of the stakeholder agencies have requirements, guidance, and procedures for demand forecasting models. Some of the agencies have guidance for microscopic simulation modeling. They have adopted methods for the estimation of microsimulation model demands based on demand forecasting model outputs. However, no such requirements, procedures, or guidance are generally available for mesoscopic simulation, dynamic traffic assignment, three-level multiresolution, and hybrid simulation modeling. This lack of information is a major barrier to the adoption of MRM.

Currently, agencies prescribe volume development methods and procedures for use in their States and regions. These standards, in their current forms, preclude the use of DTA-based models to forecast demands. Thus, local agencies are reluctant to replace approved procedures that have existed for years when forecasting facility demands.

Funding Requirements/Additional Cost and Time Requirement Justification

There is obvious concern with the additional cost required for the MRM with the limited budget available to transportation agencies. This concern becomes even greater with the uncertainty associated with additional cost and time requirements. Agencies would like to have cost estimates based on the modeled network parameters, such as number of zones, number of intersections, and number of scenarios[3]. This information supports their decisions to use MRM. In addition, inadequate budget estimations and required resources influence the probability of getting the anticipated products from MRM.

In the conversions conducted as part of the state of the-practice, the feedback from agencies that have experience with MRM described significant effort to set a full MRM as opposed to the one-directional linking of the demand forecasting model to facility-level microscopic simulation. This situation is particularly true for large-scale networks and when integrating with ABM, as with the experience in San Francisco[4], Nevada[5], and Atlanta[6]. However, the agencies also reported that microscopic simulation for larger networks, even without the use of DTA, takes extremely long to calibrate and run.

Coding midsize networks in mesoscopic DTA integrated with microscopic simulation seems to require a few weeks, if not months, of project teamwork. However, the integration of an ABM with traffic microsimulation or DTA model requires a 1- to 2-yr project. Such integration appears more feasible for small- to midsize cities. Nevertheless, the agency should recognize that

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[1] McClanahan, Doug and Brian Walsh (WSDOT); phone interview conducted by Mohammed Hadi, Xuesong (Simon) Zhou, and David Hale (research team) in the spring of 2020.

[2] Paradkar, Raj, Kavita (Boddu) Chapuri, and Steve Weller (contractors for VDOT); phone interview conducted by Mohammed Hadi, Xuesong (Simon) Zhou, and David Hale (research team) in the spring of 2020.

[3] Haskell, Vicki and Benjamin Rouleau (WisDOT); phone interview conducted by Mohammed Hadi, Xuesong (Simon) Zhou, and David Hale (research team) in the spring of 2020.

[4] Castiglione, Joe (San Francisco County Transportation Authority); phone interview conducted by Mohammed Hadi, Xuesong (Simon) Zhou, and David Hale (research team) in the spring of 2020.

[5] Ahiamadi, Samuel (NDOT); phone interview conducted by Mohammed Hadi, Xuesong (Simon) Zhou, and David Hale (research team) in the spring of 2020.

[6] Rousseau, Guy (ARC); phone interview conducted by Mohammed Hadi, Xuesong (Simon) Zhou, and David Hale (research team) in the spring of 2020.

there is also a large cost associated with using the wrong tool, as it may lead to the wrong decision.

Some agencies mentioned that the cost is not a primary concern if they apply MRM when necessary and when there is a clear benefit. One example of a clear benefit would be when evaluating a system for a congested network that results in significant changes in driver behaviors, such as diversion due to changes in managed lane pricing or the impacts of BRT. The agencies mentioned that some of these projects require a very large budget to construct, and the simulation modeling will only constitute a small fraction of the budget. Thus, the higher cost associated with MRM is acceptable as long the effort produces results that reduce the associated uncertainty. Some agencies mentioned that the uncertainty in the additional time requirements can be more of a concern than the cost due to the tight time schedules associated with these projects[7]. The contacted agencies feel that MRM is not appropriate for lower congestion and rural networks. In addition, when the analyst anticipates that no significant route path diversion will occur, MRM is not appropriate.

Model Archiving and Maintenance

Transportation agencies, including metropolitan planning organizations (MPO) and State agencies, have detailed processes for maintaining and updating their demand forecasting models. Analysts use these regional and statewide demand models for all projects that require demand forecasting in the region or the State. The demand forecasting models are peer reviewed and regularly updated using established processes. On the other hand, mesoscopic and microscopic simulation models are usually not archived and maintained; in many cases, analysts develop new models for all new projects, even though colleagues may have developed models in prior work. Only a few agencies have considered or started to archive the developed microscopic simulation models[8]. However, these agencies do not maintain or update these models[9].

The development of larger-scale, higher-cost microscopic simulation, mesoscopic simulation, and multiresolution models have motivated agencies to adopt the concept of developing the model once and using it multiple times[10]. An important reported benefit of building a large-scale MRM model is that building, archiving, and maintaining such a model allows the agency to reuse it for multiple applications, thus potentially reducing future modeling costs. As such, the authors recommend introducing a requirement in the agency business process to archive and maintain simulation models. The contacted agencies provided an additional recommendation to the model archiving and reutilization mentioned in this section. They recommended that, following any enhancement of an archived model for individual projects, analysts further archive such enhancements within the master model for future use.

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[7] McClanahan, Doug and Brian Walsh (WSDOT); phone interview conducted by Mohammed Hadi, Xuesong (Simon) Zhou, and David Hale (research team) in the spring of 2020.

[8] McClanahan, Doug and Brian Walsh (WSDOT); phone interview conducted by Mohammed Hadi, Xuesong (Simon) Zhou, and David Hale (research team) in the spring of 2020.

[9] Paradkar, Raj, Kavita (Boddu) Chapuri, and Steve Weller (contractors for VDOT); phone interview conducted by Mohammed Hadi, Xuesong (Simon) Zhou, and David Hale (research team) in the spring of 2020.

[10] Ahiamadi, Samuel (NDOT); phone interview conducted by Mohammed Hadi, Xuesong (Simon) Zhou, and David Hale (research team) in the spring of 2020.

Given the additional benefits from archiving the models, the contacted State agencies highlighted a potential problem in that the archiving of models will require the consideration of model maintenance and update needs. In the case of demand forecasting models, most agencies have maintenance and update processes, but there are no such processes developed and implemented for simulation models. The update and maintenance of demand forecasting models will need to recognize that the updates to demand forecasting models in the region will result in the loss of linkage to the lower level models.

Contracting and Procurement

As agencies start using MRM, they will face contracting and procurement issues. Agencies would like to understand the conditions under which MRM is justified, the overall cost, appropriate period of performance, desired qualifications of the selected consultant teams, and the peer-review practices.

PERFORMANCE MEASUREMENTS

Modeling tools produce a variety of performance metrics that can help to calibrate the models and support agency decisions. Analysts can calculate additional performance metrics by processing other outputs from the tools. Understanding the methods is helpful to calculate these metrics and the consistency in their definitions and calculations, as discussed in the following sections.

Definition and Estimation of Performance Metrics

Examining the definitions of the performance metrics and their calculations at different levels of the MRM and hybrid simulation models is helpful. The NCHRP 03-85 project (NCHRP 2010) addressed the consistency of metrics produced by simulation tools and by the HCM (Transportation Research Board 2016). The 2010 version of the HCM introduced the findings from that project (Transportation Research Board 2010).

In addition to the mobility metrics that are the main outputs of the commonly used AMS tools; there is great interest in efficient and effective methods to estimate reliability, emissions, and safety based on the results of the MRM. Analysts can use the Surrogate Safety Assessment Model (SSAM) tool developed by FHWA to estimate surrogate safety measures based on vehicle trajectory outputs from microscopic simulation models (Federal Highway Administration 2008). Analysts can also use demands, operating speeds, and other macroscopic measures estimated from macroscopic, mesoscopic, and microscopic model outputs as inputs to safety performance functions to predict safety for future conditions. Due to the limited outputs from existing tools related to these measures, some agencies and consultants have produced simplified postprocessing tools for estimating emissions.

Data Needs

Microscopic simulation uses detailed input data for traffic demands, geometry, and control. However, MRM adds additional pertinent data. First, the MRM will employ a larger network size in a mesoscopic simulation model-based DTA tool or hybrid tool to better simulate diversions in alternative tools. The increase in modeling scope likely requires a significant increase in the data collection effort (e.g., collecting signal control data for an increased number of signals, travel time data across network, and count data)[11]. To improve the modeling quality, analysts want additional data to measure and validate the strategic behaviors of travelers, including more accurate O-D matrices, path selection, and mode split[12]. Agencies also reported an increasing interest in the value of using probe data to estimate O-D demands and path selection[13,14]. However, the available sample sizes for these types of data may not be large enough when high resolution of the data is applicable in time and space[15].

Model Verification and Calibration

The FHWA *Traffic Analysis Toolbox Volume III* (Federal Highway Administration 2019) provides detailed guidance for calibrating simulation models. Examples of the guidance developed by State agencies include those produced by the DOTs in Florida, Iowa, Wisconsin, and Virginia (Florida Department of Transportation 2014; Iowa Department of Transportation 2017; Wisconsin Department of Transportation 2019; Virginia Department of Transportation 2020). However, no such documents are available for MRM. The agencies are unclear on the calibration and validation of MRM and whether or not they can apply existing calibration documents for these models.

SYSTEM AND TECHNOLOGIES

Transportation modeling and simulation tools are a key element in supporting decisionmaking for the design and operation of transportation systems. Different tools exist for different purposes and applications, and each has its own strengths and weaknesses for a particular level of modeling details. The behaviors of transportation systems involve interactions of these models among the supply and demand sides with the assistance of fast-growing computer technology.

Modeling tools, supporting tools, and methods for utilizing and integrating the tools to deliver effective and efficient modeling processes are needed. The decomposition of a process or function into smaller subfunctions and optimizing these functions can help in advancing the tool development and utilization. Analysts can also use the functional decomposition in their project analysis to determine whether a project component is on target, or if there are smaller subfunctions that are holding up the process. From a systems engineering perspective, there are two types of functional decomposition, as illustrated in figure 13.

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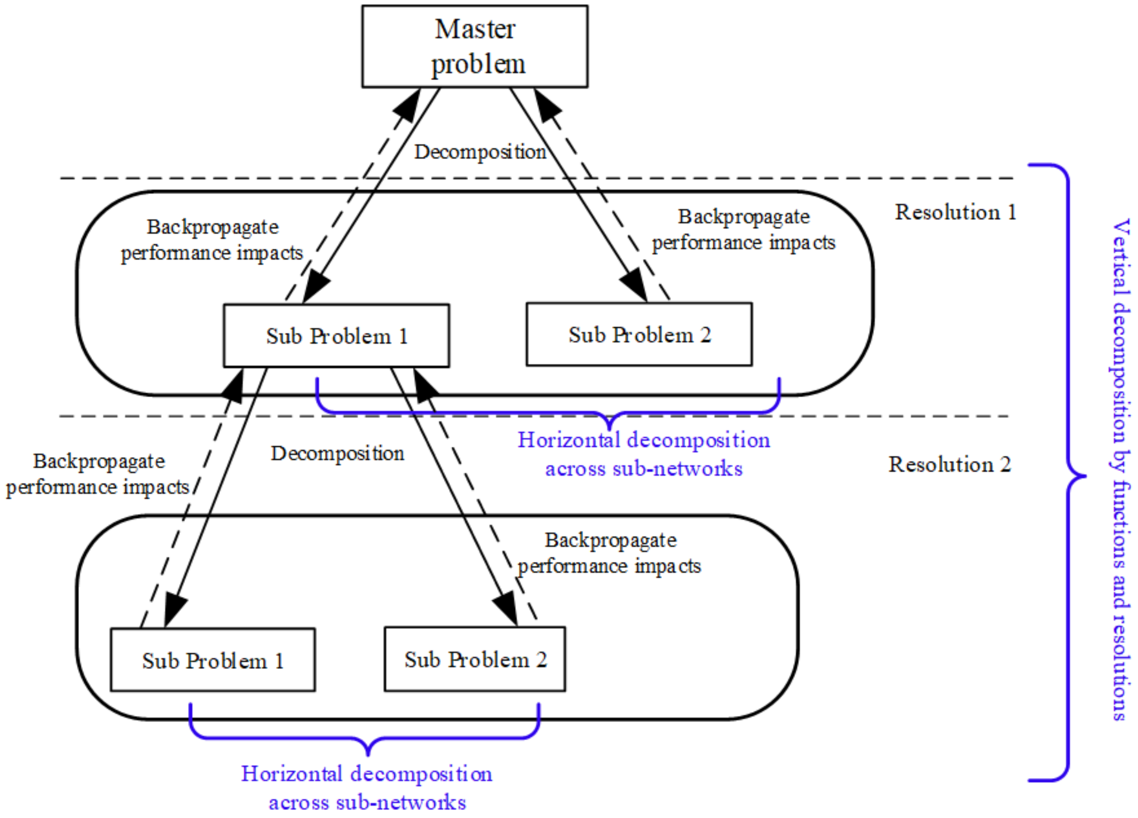
[11] Rousseau, Guy (ARC); phone interview conducted by Mohammed Hadi, Xuesong (Simon) Zhou, and David Hale (research team) in the spring of 2020.

[12] McClanahan, Doug and Brian Walsh (WSDOT); phone interview conducted by Mohammed Hadi, Xuesong (Simon) Zhou, and David Hale (research team) in the spring of 2020.

[13] Haskell, Vicki, and Benjamin Rouleau (WisDOT); phone interview conducted by Mohammed Hadi, Xuesong (Simon) Zhou, and David Hale (research team) in the spring of 2020.

[14] Warren, Andrew (ARDOT); phone interview conducted by Mohammed Hadi, Xuesong (Simon) Zhou, and David Hale (research team) in the spring of 2020.

[15] Paradkar, Raj, Kavita (Boddu) Chapuri, and Steve Weller (contractors for VDOT); phone interview conducted by Mohammed Hadi, Xuesong (Simon) Zhou, and David Hale (research team) in the spring of 2020.



Source: FHWA.

Figure 13. Flowchart. Vertical and horizontal decomposition concepts.

Vertical decomposition (or vertical stacking) aims to decompose the original problem into a sequential set of functional modules. In contrast, horizontal decomposition (or horizontal cascading) typically aims to decompose a large-scale network into geographically connected subnetworks. In the field of operations research, a master original problem can decompose into different subproblems through resource/task allocation associated with shared resources. Conversely, based on system performance impacts at the spatial and temporal scales of interest (e.g., traffic delay at macro, meso, and micro levels), each subproblem can send pricing messages in a backward-propagation manner to the master problem in order to adjust the master plan at the upper level (Chiang et al. 2007).

Furthermore, the adoption of functional decomposition in the MRM integration architecture can be built on a common understanding of the world and its constituent components. In particular, analysts can conduct the decomposition from specific perspectives of transportation network representations, demand for mobility, and multimodal system supplies (e.g., freeway capacity, traffic control policies, and transit service plans).

Typically, general transportation modeling can vertically decompose into the following modules: ABMs and macroscopic, mesoscopic, and microscopic models, based on the resolutions or fidelity at which network, demand, and supply are represented. Table 3 lists specific representations of network, demand, and supply in different levels of models.

Table 3. Representation of networks, demand, and supply in different levels of models.

Model Type	Network	Demand	Supply
Activity-based model with STA	Zone-to-zone graph between activity locations	Trip list that links to household and traveler identity and describes travel activity, travel mode, origin activity location, destination activity location, scheduled departure time, expected arrival time, and so on.	Aggregated LOS skim: i.e., travel times expressed as the complete trip time between origin and destination, for different modes (e.g., truck, SOV, HOV).
Macroscopic model (e.g., STA)	Macroscopic network without detailed representation of movements at intersections	Both internal and external zone-to-zone O-D volumes of different modes (SOV, HOV, truck, etc.) for different peak periods (a.m., midday, p.m., night).	1. Capacity (or ultimate capacity) and LOS (A–F) of links in HCM. 2. Volume delay functions (e.g., standard bureau of public roads function, Davidson's function, conical function, and Akçelik function). 3. Turn penalty table.
Mesoscopic model (e.g., DTA in regional or subarea networks)	Mesoscopic regional network with directional links and extended intersection representation	Both internal and external time-dependent zone-to-zone O-D volumes of different modes (SOV, HOV, truck, etc.).	1. Capacity and time-varying discharge rates under the time-varying density (spatial queue) on the flow-density fundamental diagram. 2. Volume delay functions to express signal delay determined by signal timing plans.
Microscopic model (e.g., cellular automata-based traffic simulation)	High-resolution network with microcells to express detailed movements and lane changing	Use path flows found in the mesoscopic network as a time-dependent demand for the microscopic network.	Microcells' capacities are determined based on microscopic parameters (e.g., reaction time, headway).

The remainder of this section identifies the gaps associated with MRM functions, associated tools, and methods. These functions include the integration and data conversion between different modeling levels, MRM, multimodal modeling, modeling of emerging technologies, assessment of various levels of behavioral responses to advanced technologies and strategies, simulation/model coupling for real-time management applications, and feedback loops for internally consistent cross-resolution traffic representation.

Integration and Data Conversion Tools

A main MRM challenge is the effort required to convert the data from one modeling level or component to another level. Additional developments could support this effort. To integrate different levels of models, the developer can systematically identify internal and external functional interfaces to exchange the performance measures of higher-level models with lower-level models and vice versa. Three types of consistency can help to ensure seamless data conversion: network interfaces, demand interfaces, and supply interfaces.

A typical example of a widely used interface is the network interface that involves the data conversion from a macroscopic network to a microscopic network. An important approach to avoid potential network inconsistency across different layers is to introduce lane-based network representation in mesoscopic simulation. With such representations, macroscopic links can uniquely map to mesoscopic lane elements. Meso segments can further discretize into cells or map to a space-continuous road representation at the microscopic level.

Demand interfaces require tools to convert different levels of desired trip data. For example, trip lists are used to link household/traveler identity and describe travel activity, travel mode, origin activity location, destination activity location, scheduled departure time, expected arrival time, and so on. Analysts can aggregate the individual-based travel records from ABM to time-dependent O-D volume for DTA and input DTA-generated path flows to microscopic simulators as static routes or turning movement counts.

As an important example of supply interfaces, scalable and consistent representation of junction control data (i.e., signal timing) is critical to the success of MRM. As there are inherent relationships between the capacity at the macroscopic traffic-flow level and signal timings, time headways, and reaction times; tools are needed to address the potential inconsistent supply-side representations across different resolutions.

Furthermore, transportation problems are multidimensional and include elements such as congestion, emissions, safety, and land use. Many emerging initiatives such as ATDM, ICM, and CVs have evolved to require evaluation tools that are sensitive to both supply (or operational performance) and demand at local and regional levels. This requirement creates a motivation for integrating multiresolution AMS tools to support alternative analysis and the development of MoE. The MRM approach can leverage the engineer's modeling capability by combining strengths across spatial and temporal regimes. As such, the integration tools can, for example, estimate the impacts of advanced applications on capacity based on microscopic modeling and feed the results to the macroscopic models.

It is notable that MRM or database conversions may only be helpful under certain scenarios. The user can begin with the end in mind, which can include a testing and validation plan for determining the success of the process. The user may have a reasonable familiarity with the domains and resolutions (i.e., macro, meso, or micro) of the envisioned AMS tools to understand strengths and limitations of the data that the integration tool or AMS data hub import and export.

As many different industrial standards are widely adopted in practices, customized preprocessing tools are still required to bridge gaps in data conversion before importing to an AMS data hub. For example, the modeling community should convert the navigable network from GIS vendors, and signal control data following the National Electrical Manufacturers Association format, to the common modeling specification in transportation AMS studies, e.g., General Modeling Network Specification (GMNS) (Ziering 2007). It is also very important to clearly identify potential inconsistencies and define steps, even at a high level, to handle inconsistencies. An established and well-documented process could be very useful for agencies to continuously refine a collection of tools, rather than simply applying ad hoc processes for each project when a model is applied.

MRM Tools and Methods

The individual modeling components of MRM still have gaps to address or recognize. The gaps include the modeling tools themselves, the recognition of capabilities, and the applicability of modeling tools in relation to various use cases.

Agencies in the United States have widely used macroscopic four-step travel demand models for decades. They employ a four-stage, sequential algorithm. An advantage of the four-step model is that it is a feasible way to reduce the extremely complex system of traveler behavior into analytically manageable components. The four-step model can deal with relatively simple techniques and reasonable amounts of data. From the AMS perspective, some limitations of the four-step travel demand model include:

- It cannot model decisions of individuals, effects of the VOT and reliability, continuous times-of-day variations on travel, and goods movement.
- It produces a single answer and cannot handle uncertainty in model estimates, partially due to observed variations.
- It is often used by analysts to represent an overall year based on a typical day.
- It may lack consistency among different levels of elements in the modeling trip chains.

Mesoscopic simulation-based DTA models are becoming a popular option for many planning and operations applications. The primary application areas for DTA models are significant changes of roadway configuration (e.g., change downtown streets from one-way to two-way configuration), freeway expansions, construction of a city bypass, addition or conversion of HOV/HOT lanes, integrated freeway or highway corridor improvement/construction, and TDM strategies such as peak spreading or congestion pricing. Unlike the macroscopic traffic assignment model in which volume can exceed roadway capacity and capacity values do not reflect traffic flow dynamics, DTA uses true capacity constraints on the upstream and downstream movement performance over time. Thus, simulation-based DTA can produce a better evaluation of alternatives than the macroscopic traffic assignment. Furthermore, DTA can better account for signal control impacts. When it comes to a complex scenario evaluation, analysts can integrate DTA with other models to perform analysis using manual techniques or customized utility functions.

The challenges of the mesoscopic DTA models mainly include the following:

- Challenges to prepare O-D matrices for mesoscopic DTA models. Traditionally, there are two methods to generate the (time-dependent) O-D matrices for the DTA models. One method is to extract the (time-dependent) O-D matrices from the outputs of upper–level models (e.g., ABMs or four-step models). The second method is to estimate the O-D matrices using sample Bluetooth/Wi-Fi/mobile phone data. Analysts have also used ODME procedures based on a seed matrix and traffic counts to estimate the O-D matrices. It is still theoretically challenging to systematically integrate heterogeneous data to produce a reliable demand representation of mesoscopic models.

- Challenges to generate consistent demand and supply representations in a subarea network. Because of the computational burden of the DTA models, analysts typically extract a mesoscopic subarea network from external GIS files first and then manually supply detailed junction and movement data. A streamlined process of converting the original regionwide static O-D demand to the time-dependent subarea O-D or path flow is critically needed for DTA deployment, in conjunction with the automated tool for converting a link-based network to a lane-based high-fidelity representation.

In the United States, conventional travel demand models are slowly moving forward to the new generation of behaviorally realistic ABMs. The main characteristics of ABMs versus conventional travel demand models (trip-based models) are:

- Tour-based models versus trip-based models: A tour is a closed chain of trips starting and ending at the anchor locations. The tour-based model records trip dimensions (mode, destination, and time of day).

- Microsimulation models versus an aggregate approach: Analysts can use microsimulation models in the tour-based model. The authors do not recommend applying a tour-based model on an aggregate approach due to the difficulty of capturing internal sensitivity, population, and travel segmentation.

Some limitations of the ABMs include:

- The relative complexity and time-consuming process of the new model are obvious disadvantages to the practitioners. Successful demonstration of the practicality and improved forecasting accuracy of ABM is thus necessary for ABM research.

- The size and quality of household surveys is the most limiting factor for the activity-based microsimulation structure. Home interview survey data are very expensive to obtain.

Another important issue related to MRM is the selection of appropriate tool(s) for specific applications. According to different temporal resolutions, analysts can further examine existing AMS tools according to their capabilities in reproducing real-world performance and running speed, as well as real-time updating, as shown in table 4. The selection of tool level and specific tool(s) will require close examination of tool capabilities to satisfy specific project requirements.

Table 4. Transportation modeling capability along temporal resolution.

Model Type	Capable of Replicating System Performance?	Running Speed?	Receive Real-time Information and Simulate Nonrecurring Events?
Macroscopic travel demand models	Yes, on a planning level network	Reasonable running speed for a large network	No
Mesoscopic models	Yes, on the subarea network level	Longer than macroscopic travel demand model	Yes
Microscopic models	Yes, on a small network	Needs significant running time	Yes
Static deterministic programs	Yes, on nodes and link level	Fast	No

The applicability of the modeling tools depends on various use cases of transportation decisionmaking. These challenges are multimodal and diverse by geographic location and temporal elements. They include interrelated influences on the system from traffic demand, transportation capacity/supply, economic market forces, land-use allocations and decisions, and environmental conditions. Table 5 presents a summary list of use cases, typical user agencies that may be involved, current practice, and improved practice. The development and use of the AMS MRM and a data hub could drive the improved practice.

Table 5. Data hub use case examples.

Use Case	Typical User Agency	Current Practice	Improved Practice via MRM and Data Hub
Long-term planning	MPO	TDM with a static assignment	Integrate with DTA, emissions, safety, economic, land-use models, and field data
Prioritization of projects	MPO, DOT, local agencies, transit	TDM	Integration with DTA, provide feedback to land use, activity based, emissions, and safety models
Corridor planning	DOT, transit, local agencies	TDM, HCM, and sometimes microsimulation	Integrated bottleneck identification tool with mesoscopic-simulation-based DTA and microsimulation
Construction sequencing, detour impact	DOT	No analysis or microsimulation	Integrated bottleneck identification tool and microsimulation field data, predictive scenario planning, and active traffic management.
Congestion hotspot	MPO, DOT	TDM or field observation	Integration of bottleneck identification tool, mesoscopic simulation-based DTA, and field data
Traffic impact study	DOT, local agencies, property owners	TDM and HCM	Integration of TDM, HCM, safety, land use, and economic modeling
ITS evaluation and operations planning	DOT, MPO	TDM	Integration with mesoscopic simulation-based DTA and microsimulation, field data, predictive scenario planning, active traffic management
Transit network improvement	Transit agency, MPO	TDM	Mesoscopic simulation-based DTA or microsimulation, feedback to activity-based models, land use, emissions, empirical operations data, etc.
Land-use planning	MPO, local agencies	Land-use model	Integrate land-use models with transportation models to reflect real relationships. Integrate with economic and emissions modeling.

Behavioral Response and Demand Modeling

In practice, travel demand models should contain fully integrated behavior models to reflect congestion and cost change impacts on the full range of traveler behaviors that impact network performance. One of the most significant gaps in the functionality of current models is the lack of behavioral response associated with congestion, pricing, and traveler information (and other demand management strategies). In a number of recently completed SHRP 2 projects, such as C04 and C10, the travel behavior models have been systematically incorporated to construct an interpretive model that can capture the influence of dynamic congestion and pricing on travelers (microscopic) and transportation (macroscopic) systems (Resource Systems Group et al. 2013, Koppelman 2013).

Another set of major impediments include a lack of consistent operational data at planning scales and practical limitations of current commercial-grade DTA software. Current practical traffic models have limited capabilities of incorporating behavior responses to congestion/cost and are generally limited in the size of the study area and the simultaneous number of vehicles.

In order to consider complex behavior responses, transportation models of all types usually require significant calibration effort to produce reasonable results. This is especially challenging for networks that are oversaturated and/or include demand management strategies that affect travelers' choice of mode, departure time, and route. By only focusing on the supply side, many transportation analyses do not reflect the true effects of operating conditions, particularly when it comes to examining performance over multiple days to estimate reliability. The development of standards, tools, and information as part of this project looks ahead to meet future modeling needs, as well as current practices.

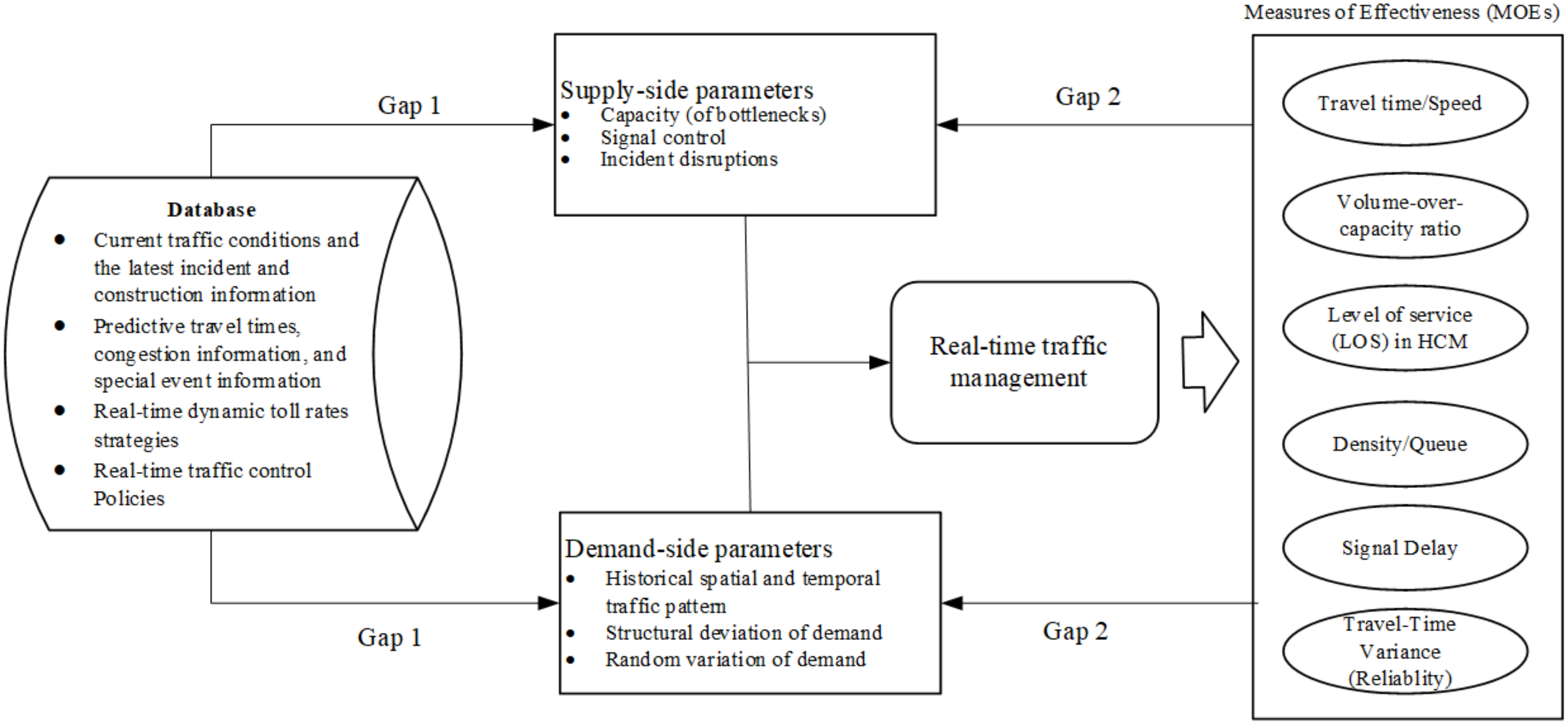
Simulation/Model Coupling Approach for Real-Time Management Applications

An integrated transportation network representation is typically used to synchronize macroscopic and mesoscopic traffic simulators, where the spatial data are defined as a set of links and nodes. Nodes are point locations along the network where traffic flow originates, terminates, or transmits, while links are connections between nodes. GIS network databases are available from commercial map data vendors. Commercial vendors of GIS software typically license and integrate data products from multiple sources (e.g., U.S. Census and commercial data vendors).

To capture traffic dynamics, real-time information on current and near-term future conditions and operations is a critical element of traffic management. The USDOT ICM program demonstrated the use of model-based applications as predictive engines to support traffic management and operations at the US–75 corridor in Dallas and the I–15 corridor in San Diego. ICM aims to proactively utilize the multimodal capacity, including parallel roadways, HOV, and transit services, to improve system performance. Developers have integrated a number of AMS and MRM tools for offline design and evaluation and for real-time activation of different ICM strategies (Klim et al. 2016).

Another potential use of MRM in real-time traffic management includes signal optimization for vehicles with various connectivity capabilities. TMCs receive continuous data feeds from system detectors recording traffic volume and speed across individual lanes in increments as low as 1 min or less. Additional data will become available from CVs. The collected data, combined with data from the traffic signal controllers, can feed into signal optimization software to produce traffic signal timing plans for implementation.

Two types of gaps exist in a simulation/model coupling for real-time traffic management, as shown in figure 14. The first type of data-to-model gap relates to capturing the historical traffic pattern (time-dependent O-D volume), structural deviations of demand, and daily random variations of demand. This gap also relates to providing an effective and stable method to calibrate real-time demand and the capacity of bottlenecks and to identify capacity drops caused by incident disruptions. The second type of gap is about how to integrate both supply- and demand-side elements in the simulation/model coupling system for real-time traffic management. Modelers should use the MoEs in a feedback fashion for recalibrating the key parameters. When applying such integrated modeling systems, the analyst can pay extra attention to ensure stack stability and model scalability toward greater predictive accuracy.



Source: FHWA.

Figure 14. Flowchart. Gaps in coupled simulation and demand management systems.

Thanks to the SHRP 2 research efforts mentioned earlier such as C04 and C10, multiple formulations of demand models that estimate user response to travel time and cost changes at 5 min to daily scales are available, both fully integrated and loosely coupled with dynamic network models. The emerging simulation/model coupling approach brings opportunities and challenges to the core functions of traffic demand estimation and control. For example, analysts have applied DTA simulators as a surrogate-based approach (Chen et al. 2015). Figueira and Almada-Lobo (2014) described four classes of simulation/model coupling approaches: optimization with simulation-based subalgorithm, iterative method, sequential method, and simulation with optimization module.

Many existing traffic modeling/simulation methods mainly focus on macroscopic point bottleneck performance and corridor-level, travel-time estimation. These models will benefit from the availability of methods and data to allow the validation and calibration of network-level models. There are few reliable, computationally efficient data mining and model calibration methods for utilizing emerging Bluetooth and GPS data sources to estimate route-based travel times, or for obtaining microscopic speed variation and vehicle acceleration/deceleration information, which is critical for emissions and system reliability analysis. The new generation of smartphones and future availability of CV data will present a data-rich environment. This environment will allow transportation demand modeling and traveler information systems to thoroughly and accurately measure individual driver behaviors and networkwide traffic flow evolution. However, additional data mining and management tools would help use mobile traffic probe data in their early deployment stage, as low market penetration rates of mobile data could lead to small data samples in statistical reference, and, thus, high variances in travel time and network-flow estimates.

A number of demand calibration tools (e.g., open-source packages, Biogeme, and Apollo) can also provide information about the behaviors of travelers. There is great interest from the transportation planning community to apply emerging machine-learning tools along this line.

Table 6 lists a summary of different simulation/model-coupling approaches. Essentially, there are a number of important issues to examine when selecting a real-time simulation/model-coupling implementation method, including:

- How does transaction load affect run time?
- How does each software module ensure stack stability?
- How can developers construct uniform conceptual models of vehicle attributes?
- How can different resolutions of traffic simulators represent lateral and longitudinal road space?

Additional considerations may include model and implementation process scalability, potential limits on network size or number of vehicles, as well as time and clock management mechanisms for real-time systems.

Table 6. Comparison summary for real-time simulation/model coupling approach.

Approach	Key features	Advantages	Disadvantages
External executables/stand-alone programs.	Use text file as input and output between programs. Configuration file or batch file to control iteration flow. Call perform manual iterations using difficult programs.	No change to existing programs. Easy programming calling on the same machine. Easy to debug by analysts and modelers.	Ad hoc one-to-one program interface. Extensive file exchanges. Loose coupling between programs. Difficult to have effective time and clock management across different tools.
Static or dynamic programming library. API, DLL, COM.	Users provide simulation-callable DLL. Simulation programs will embed the user-defined library during the execution of application.	Unified programming interface. Efficient integration for specific functionalities, such as signal timing control or vehicle statistic calculation (trigged by vehicle movement functions).	Relatively limited functionalities. Require familiarity of debugging and efforts for maintenance. Only supports data exchange on the local machine.
Message passing and interprogram data sharing. Common Object Request Broker Architecture.	Use interface definition language to specify a mechanism in software for standardizing the method-call semantics between application objects.	Written in multiple programming languages. Integrate large-scale simulation programs running on multiple computers/different platforms.	Extremely complex computing environment with sizable challenges for development, integration, verification, calibration, acceptance, application yield, and maintenance.
Web service in cloud computing.	Service providers pool the processing power of multiple remote computers in a cloud to perform simulation/modeling tasks.	Allow integrated data collection, data sharing, and traffic modeling. Perform simulation tasks might normally be difficult, time-consuming, or expensive for an individual user or a small company to accomplish, especially with limited computing resources and funds.	Only suitable for routine tasks with extensive user debugging. Difficult for modelers to debug and examine simulation results. Potential issues of network bandwidth or platform maturity.

API = application programming interface; DLL = dynamic linking library; COM = component object model.

Data-Related Modeling Challenges

While the leading-edge research that is underway will significantly advance transportation modeling practices, the research team's review of current AMS tools has shown that integrated modeling practices in transportation are largely ad hoc and relatively inefficient. Many of the challenges revolve around data, specifically, data availability, quality, format, exchange, and system coupling.

Data Availability

The types of data used for inputs into models are sometimes not available or are difficult to obtain, particularly for arterial streets and freeway off-ramps. A wave of new data sources, particularly probe-based data sources such as Bluetooth, data from private vendors, and real-time data from traffic signal controllers, are becoming increasingly available for use in transportation modeling. However, these data sources are not yet widely integrated into standard modeling practices and still require significant labor resources to compile, scrub, and convert the data to a useful format.

Common Platform for Data Exchange

MRM modeling requires exchanging large volumes of data. Until recently, the lack of standardized data formats for common elements (e.g., O-D volume, turning movement, vehicle trajectories, and, to a lesser extent, roadway network data) led to manual manipulation or customization of utility tools to interface between models. This situation increases the risk of error in transposing data inputs. The additional effort also takes away from time analysts could spend on calibration/validation, running additional scenarios, and performing sensitivity tests. Many of the AMS tools have proprietary components encumbered by copyrights or other restrictions. These limitations create impediments for exchanging data across independent software packages and lead to the development and application of individual utility tools. Furthermore, scalable and consistent representation of junction control data (i.e., signal timing) is critically needed for the success of MRM.

One solution to this challenge is to develop an open-data format that allows software vendors to implement data conversion utilities from their own proprietary format. This approach was taken for the open matrix (OMX) file format (OMX 2020). Specifically, an OMX format is a structured collection of two-dimensional array objects and associated metadata. The specific layout ensures that the matrix data can be stored and retrieved correctly and efficiently with complete and consistent information. For maximum effectiveness, users could develop open-data formats through a publicly visible, vendor-independent process, interoperable among diverse traffic modeling and simulation tools, sufficient and unified in its representation at various spatial and temporal scales. For example, the recent GMNS effort defines a common human- and machine-readable format for sharing routable road network files (Volpe, FHWA, and Zephyr Foundation 2020). NCHRP Project 20-64 also developed TransXML—a family of transportation data exchange formats using the eXtensible Markup Language—as an enabling technology for data interoperability (Ziering 2007). To fully integrate multiple stand-alone models or simulation tools, it is helpful to standardize data exchange between those tools at different levels of resolution. Moreover, an open standard may enhance the interoperability of AMS tools to coordinate and work together in a common (virtual) environment.

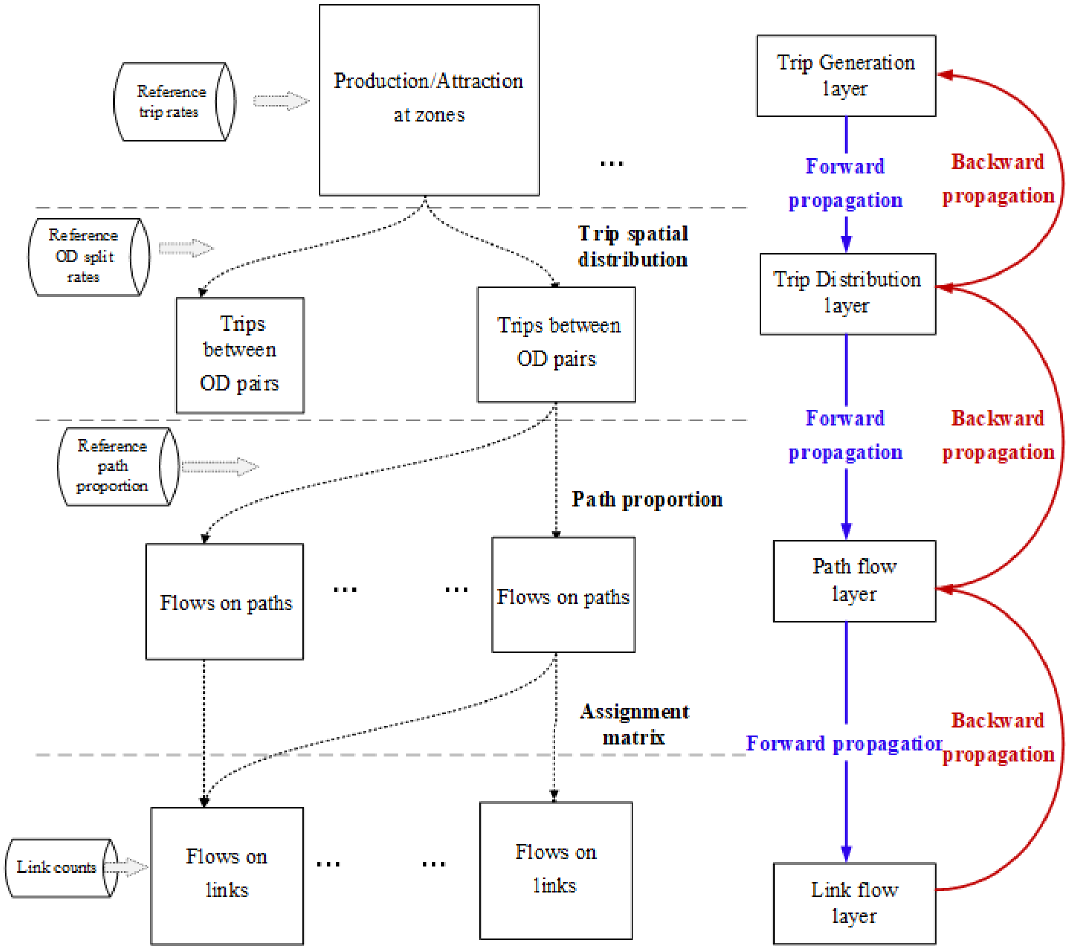
Common Conceptual Model

Data format specifications and common data platforms are useful but not sufficient for a fully successful MRM integration. It is vital to develop a common full integration of conceptual (time, space, transaction) alignment and run-time integration (e.g., joint solution versus iteratively reconciling independent solutions). The conceptual models can recognize significant limitations in the application stack for macro, meso, and micro implementations. Models of transport demand currently rely on an incomplete representation of network performance; models of network traffic operations have an incomplete representation of travel behavior responses. One example of conceptual alignment is that analysts usually enter traffic assignment inputs as daily or peak-period traffic demands, while the HCM estimates link capacities based on hourly data. Then an hour-to-period factor is required to convert hourly capacity to period capacity. Furthermore, planners also require data consistency checking tools to identify possible inconsistencies from data sources.

In the operations research and machine-learning community, computational graph (CG) is a widely used framework for enabling forward and backward propagation between different data representation layers. Many open-source machine-learning libraries (e.g., Tensorflow) have incorporated CG to derive estimator residuals of different data sources. Transportation demand modeling can conceptually apply CGs, similar to integrated four-step modeling efforts, as shown in figure 15 (Boyce, Zhang, and Lupa 1994); (Yang, Meng, and Bell 2001). The forward-passing process sequentially performs four-step methods, and the backward propagation inversely implements various types of feedback loops on the forward-passing process.

System Coupling

Although a full integration approach that builds on the same design is desirable for MRM, this approach would involve both a common conceptual model and a common data model, plus single-user interfaces for GIS and other data analysis software. Tight coupling means modules are dependent on one another tightly, while loose coupling indicates the relative independencies of the modules. The future integrated modeling approach to be developed should select either a loose-coupling approach or a tight-coupling approach based on various considerations such as real-time response requirements and data availability. Utility tools serving the transfer of data files back and forth between different resolutions of common models can be well defined and designed to be scalable, modular, interoperable, and extendible. Developers can build the individual models on a modular basis. As such, developers can easily connect and extend each module to meet future modeling needs.



Source: FHWA.

Figure 15. Flowchart. CG in transportation demand modeling to represent the four-step method and its feedback loop.

Internally Consistent Traffic Representation

Software developers are enhancing the functionality of their suite of programs to enable integrated and MRM to act as a one-stop shop for modeling needs. However, given the lack of industrywide data standards and protocols, it is generally not feasible from a time and resource perspective for practitioners/agencies to work across multiple software-developer packages relying on a proprietary, vertically integrated application stack. A reliable integration of open-source tools also calls for long-term professional maintenance and an internally consistent MRM framework. This need underscores the driving motivation to establish information, standards, and protocols to address data handling and exchange.

The biggest inconsistency regarding the ability of MRM to replicate system performance lies in the behavioral response, particularly for congested networks, which are of more interest to transportation agencies than uncongested networks. Furthermore, MRM also lacks tools and information for calibration/validation and evaluation of demand-responsive strategies, which are of more interest to agencies, given the fiscal and environmental constraints.

Leading-edge research projects are investigating behavioral response effects, and these will likely continue to evolve over time. However, useful calibration/validation tools for MRM remain unavailable. Based on open datasets (e.g., publicly accessible planning networks and sensor data and vehicle trajectory databases), an open-source and clearly documented MRM integration demonstration platform would be highly desirable and useful for practitioners. The combination of open test beds and open-source models could allow transportation analysts and researchers to better understand the underlying, complex modeling approach and further freely modify, enhance, and incorporate the utilities to meet varying needs of users and new modeling challenges.

Software developers are advancing integrated modeling techniques through enhancements to their existing suite of proprietary software packages to capture performance at an individual vehicle level. However, the feedback loop with travel demand choices is limited. As stated previously, one of the most significant gaps in the integrated modeling process is the ability (or lack thereof) to model the demand effects of operational conditions without significant intervention.

For a subarea study, one could simply extract vehicle path data from macroscopic planning or mesoscopic DTA tools and feed the data into a microscopic simulation model to generate second-by-second vehicle speed and acceleration output for detailed emissions or mobility-related analysis. Nonetheless, there are multiple impediments associated with such a loose linkage or potential inconsistency between macroscopic/mesoscopic traffic flow models used in DTA systems and microscopic car-following and lane-changing models used in traffic simulation tools. The low-resolution traffic flow models are a reasonable approximation to complex real-world traffic flow dynamics. However, it is notable that by simply mixing models with different resolutions, microscopic traffic simulation results could be significantly different from the link performance statistics previously obtained from the macroscopic/mesoscopic assignment.

Modeling of Advanced Strategies and Emerging Technologies

The modeling of advanced strategies and emerging technologies is still an area of research, particularly for the modeling of CAVs and emerging mobility options like MaaS and micromobility. Further research and development will investigate and model the traveler behaviors used for different levels of modeling, ranging from demand forecasting to mode, route, and time shifts, to microscopic traffic flow characteristics.

ORGANIZATION AND WORKFORCE

Effective utilization of MRM involves qualified staff to develop, calibrate, and peer review the developed models. Most of the user and vendor feedback reported that the lack of experience, background, and training are major barriers to the use of MRM. There is a strong incentive for workforce development, including recruitment, retention, and training, to support the MRM effort.

Staffing/Lack of Experience Background

In general, public agencies and consultants have built good experience and knowledge in demand forecasting models, particularly in the conventional four-step models, which have been widely used to estimate travel demands on current and future networks in the United States for decades (Chiu et al. 2011). Agencies desire more experience and knowledge in activity-based modeling. Regarding microscopic simulation, public agencies have relied in part on consultant experience. As mentioned by most public and private agencies contacted as part of this project, these consultants have generally good experience in microscopic simulation. However, public agencies are recognizing that they can build some experience in microscopic simulation to at least be able to manage projects and review the activities and products of the simulation effort. Building this experience will become even more challenging with MRM, where the staff will have to understand the full spectrum of models, including data analytics, demand forecasting, analytical procedures, mesoscopic simulation-based DTA, and microscopic simulation.

Staff Retention Issues/Retirements

The retention of employees to prevent the loss of the acquired experience is a major challenge. The contacted public State agencies identified the retention of employees in the public sector as an issue, as the public agencies may have difficulty in recruiting and retaining the qualified staff. Acquired experience can also be lost due to retirement.

User Training

MRM involves the expertise and knowledge of demand forecasting and microscopic simulation models. MRM also involves acquiring additional skills and knowledge specific to MRM, including mesoscopic simulation, DTA, model integration, hybrid simulation, and discrete traveler choice modeling concepts. Currently, the demand forecasting community is not as strong in traffic flow theory and simulation concepts, based on the discussion with some State DOT representatives (e.g., the research team's discussions with staff from the FDOT[16]) conducted as part of this project. On the other hand, simulation modelers are generally weak in understanding assignment, DTA, and discrete choice models, based on statements by the same FDOT representatives. Thus, a strong training program is desirable to bridge the gap.

COLLABORATION

Collaboration is an important dimension to support successful MRM, as described below.

InterAgency and Intra-Agency Collaboration

Phone discussions conducted as part of this project indicate a disconnect within the same agency between demand forecasting modelers and simulation modelers. There is a "stovepiping" problem between the modelers of different resolutions and different organizations. In the cases when demand forecasting and simulation need to interface, the modelers on both sides may not work close enough to produce an effective model. Stakeholders mentioned similar issues

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[16] Learned, Jason and Jeremy Dilmore (FDOT), phone interview conducted by Mohammed Hadi, Xuesong (Simon) Zhou, and David Hale (research team), in the spring of 2020.

regarding the interface with the demand forecasting modeling done at MPOs. However, the use cases for long-range forecasts and conformity are different from corridor studies and project traffic forecasting. It is not unusual for MPOs to do work for hire in support of corridor studies and project forecasts. Also, it is quite typical for a State DOT to provide forecasting for small MPOs and non-MPO areas.

The above-mentioned separations appear to exist in many regions, although the degree of the separation varies, depending on the region. MRM will entail more collaboration and interaction between modelers of different levels of modeling, including those within the same agencies and those at partner agencies.

Another aspect of the collaboration is how the central office of State agencies and local districts collaborate on advancing the state of the practice of simulation modeling, including MRM in the State. The level of centralization in leading the modeling practices vary by State. Both the central office and local districts can play major roles in promoting and supporting MRM.

In the conducted discussions for this project, stakeholders mentioned that the MPOs are mainly concerned with the characteristics of the planning process and the levels of detail and accuracy of their models to address these characteristics. In many cases, these characteristics do not justify the use of simulation modeling. At least one State agency and its consultants mentioned that the outputs from the demand models are too coarse and have lower accuracy compared to what is appropriate for microscopic simulation modeling. Thus, analysts may adjust the outputs from these models to produce reasonable inputs to simulation. This discussion indicates that there could be a benefit to bringing different types of modelers together to allow them to support an effective MRM.

Consultant Role

Currently, a large proportion of public agencies use consultants in their simulation efforts, as confirmed by the use of consultants by most agencies contacted in this study. This use of consultants is particularly true in the case of microscopic simulation. The public agency role in such cases is limited to reviewing the consultant modeling effort and products. In some cases, particularly for important and complex projects, the public agencies may hire a second consultant to review the simulation model development. Due to limited experience with MRM, the public agencies may face a challenge in finding qualified consultants to perform MRM in their region.

The consultants themselves encounter difficulty in building and maintaining the qualifications and experience needed, given the current low demand for MRM. Maintaining adequate expertise in MRM concepts and tools used in the region is a challenge for this reason. The costs of building experience in more than one software platform can also be a barrier, especially for smaller firms. It may also be difficult for small companies to keep multiple commercial MRM software tools due to the high cost of acquiring the software and maintaining the expertise.

CULTURE

Culture in the context of MRM refers to the degree to which the benefits of implementing MRM are valued by the transportation agency. Agencies vary in their levels of adoption and interest in simulation modeling. Some agencies feel that analytical models, such as those of the HCM, are sufficient, particularly given the low level of congestion in their areas. This variation also relates to the confidence of modelers or decisionmakers in their knowledge of and ability to review the analytical model analysis. As such, it is easier for these agencies to explain and stand behind the analysis procedures and results. There is a concern that spending additional resources on advanced modeling techniques may not produce the anticipated results if the analysts do not conduct the modeling effort correctly, and that the risk of such incorrect modeling is high.

Understanding the Tools

The feedback obtained as part of this project revealed that there may be a limited understanding of MRM, and that this limited understanding is a major constraint to a large-scale adoption of MRM. Agencies will select a model even if they recognize that it can be less effective and accurate than other models that they do not understand and cannot defend.

Understanding the Benefits

Stakeholder agencies have mentioned that they will be more willing to utilize MRM if they understand the benefits of MRM compared to their current modeling practices. The risk to go to a new, costlier paradigm may need to be justified based on benefit-cost analysis. Many of the stakeholder agencies that are familiar with the MRM concepts indicated interest in MRM and recognition that MRM may allow more realistic modeling of traffic dynamics for a larger network. The greatest interest appears to be due to the sensitivity of the MRM in modeling the changes in traveler strategic behaviors in response to traffic management and demand management policies and strategies (e.g., managed lanes, congestion pricing, BRT). They expect this interest to increase alongside the increasing need to model emerging vehicle connectivity and automation, multimodal operations, micromobility, mobility as a service, and ride hailing. However, there is a desire to demonstrate these benefits and for effective messaging that communicates the benefits and experiences to the agencies.

Need for Lessons Learned

Agencies that have no experience with such modeling framework would like access to example applications in other locations and lessons learned. The agencies are interested in knowing if the MRM produces results that make more sense and if they can defend MRM results more easily than using demand forecasting model results as direct inputs to microscopic simulation models. For example, it would be valuable to have case studies demonstrating how demand estimation via traditional methods has a lower quality than those produced by MRM.

There is a desire for better messaging of the value and issues associated with MRM since there are many unknowns and uncertainties surrounding this type of modeling. Case studies and success stories are key. MRM usually involves a relatively large effort, time, and resources compared to current practices. Thus, messaging, case studies, and reporting lessons learned become more important to reduce the risks of utilizing this modeling approach.

SUMMARY

This section assessed the gaps in MRM use based on the six CMM dimensions. The six dimensions are the business processes, performance measurement, system and technologies, organization and workforce, collaboration, and culture. The identified business process gaps are related to the needs for institutionalization of MRM use for certain types of analysis, development and provision of methodology and guidance, allocation of funding and project time to meet MRM requirements, adoption of processes for model archiving and maintenance, and enhancement of contracting and procurement practices. The identified performance measurement gaps include variations in the definitions of methods used in the estimation of various performance metrics, data needs, types, and resolutions of measures used in model calibration and validation. The gaps in systems and technology include the need for development and/or enhancement of methods and tools that support the integration and data conversion between different modeling levels, MRM tool enhancements, multimodal modeling, modeling of emerging technologies, assessment of various levels of behavioral responses to advanced technologies and strategies, simulation/model coupling for real-time management applications, and feedback loops for internally consistent cross-resolution traffic representation. The organization and workforce gaps involve the need for qualified staff to develop, calibrate, and peer review the developed models. There is a need to acquire experience and background through the recruitment, retention, and training of staff to support the MRM effort.

Collaboration gaps include interagency and intra-agency collaboration. Culture in the context of MRM refers to the degree at which the benefits of implementing MRM are valued by the transportation agency. As indicated in this document, there is still a variation in the levels of adoption and interest of agencies in MRM.

CHAPTER 9. CONCLUSIONS

Recognizing that MRM is a framework for integrating different levels of simulations, this document first provided basic definitions associated with the models that can be used as components of the MRM, support models that can be used to increase the effectiveness and efficiency of modeling, required data for modeling, multiresolution modeling, and convergence. The identified and defined convergence concepts include static and DUE, feedback and equilibrium in the integrated four-step process, and behavior UE for activity-based models.

Utilizing the above-mentioned definitions, this document then discussed in more detail important information about the basis behind the use of various traffic analysis tools commonly applied and integrated into real-world applications. The aim was to assist traffic engineers and planners in the selection of suitable types of traffic analysis tools for specific operational improvements and modeling needs. The provided information should also help practitioners understand how to integrate existing analytical and simulation tools to create a cost-effective MRM application.

The review of literature conducted as part of the state-of-practice review of this study indicates that MRM is most valuable for changes that cause regional impacts on the behaviors of travelers, such as pricing strategies, vehicle eligibility to use lanes, and lane access control. These models are also powerful in assessing the impacts of temporary capacity disruptions, such as dynamic lane control, ramp metering, and incident management. Another finding is that for large-scale analyses, there were difficulties and time constraints that limited the validation of models for a number of cases reviewed in the literature. In addition, the reviewed literature indicates that the availability of required data varies by region. The long running time of the larger and more complex models is also an issue. The reviewed documents on these large-scale models reported that the additional input information required a significant manual effort. Another major issue is that the projects require realistic zone representations and zone connections to the network. There were also challenges with dynamic transit assignment, and several issues make dynamic transit passenger assignment difficult. The reviewed studies have also reported on the importance of high-quality O-D matrices, which can be a challenge.

The reviewed studies indicated that the modeling of DMA and ATDM will benefit from further research to better understand shifting traveler choice behavior, as related to these applications. Researchers have recommended the use of clustering analysis to support multiscenario modeling of these strategies.

The modeling can also benefit from the development of tools that read vehicle trajectories from simulation and estimate different mobility, safety, and environmental performance measures in a consistent manner. The convergence of DTA should also be a major focus, since the lack of this convergence reduces the reliability of alternatives analysis based on the modeling results. Another critical issue is the need for feedback loops to ensure the consistency of different resolutions. There has been limited research on the consistency of the different resolutions. Past work emphasized the importance of preserving network consistency and correspondence (including the node identities) between the different levels of MRM. In previous studies, researchers examined consistency in terms of vehicle loading, geometry, time resolution, and traffic dynamics. Researchers argued that modelers should pursue both MBC and PBC. MBC is the degree of matching between the model outputs and MoEs under various conditions. PBC refers to maintaining consistency between model results and facility demands as conditions change.

An identified problem with hybrid simulation that involves using different simulation models in the same run is the fidelity at the boundary between such simulation models. This problem involves difficulties in the aggregation and disaggregation of vehicles that pass through the boundary. A number of studies have provided approaches to mitigate this problem.

An important aspect of this study was to determine the current experiences and thinking of transportation agencies with regard to the utilization of MRM. The team held 14 discussions with agencies that had experience in MRM and developers of MRM tools. The agencies provided valuable information on how they define MRM, how many MRM projects have been conducted, the level of effort, the limit on the MRM network size, the potential benefits and costs of MRM, the barriers and hesitation to applying MRM, the reason for applying MRM, plus existing and planned MRM features in existing tools. Most participants in these discussions gave the commonly used definition of partial MRM, full MRM, and hybrid simulation, as presented earlier in this document. Some additional configurations mentioned included the use of refined subarea models in macroscopic model-based traffic assignment, multilevel microscopic models that have different levels of detail at the region versus the focus-corridor level, ABM and DTA integration, and top-down modeling versus utilizing feedback loops. Participants reported additional efforts to set up a full MRM, compared to just going from the demand forecasting model to facility-level microscopic simulation. The required effort is a function of the network size, whether signal timing needs to be coded or not, availability of signal timing data in a consistent format for the region, and the level of detail and correctness of the demand model coding. All of the 14 participants indicated significant interest in MRM and this project. However, the research team expected this response, because they selected stakeholders who, in most cases, have already used MRM.

Discussions with the tool vendors indicate that the general level of interest does not appear as high. Most of the users and vendors reported that lack of experience, background, and training are major barriers to the use of MRM. The research team concluded that there is an opportunity to increase interest through messaging of the value of MRM, and the associated issues, since there are many unknowns and uncertainties surrounding this type of modeling.

In addition to the 14 discussions mentioned above, the project team conducted 5 teleconferences with additional agencies that have limited experience with MRM to have a more general assessment. Some of the issues and concerns of the agencies highlighted in the five discussions include the start-up costs, learning curve requirement, insufficient guidance, tools not well integrated, functions not well automated, few success stories or pilot projects, uncertainty about cost-effectiveness, current analyses using traditional methods not being challenged, and, depending on specific agency and project, little need for large spatiotemporal scopes.

The review of literature and the 19 outreach discussions conducted in this study indicate that some of the constraints and limitations are associated with the available methodologies, guidance, procedures, data, and tools available to transportation agencies. However, there are other issues related to policies, staffing, training, collaboration, information sharing, and attitudes toward simulation modeling that can significantly impact the adoption and effectiveness of MRM. Given the several dimensions and subdimensions of the gaps associated with MRM, the project team used the six dimensions of the CMM framework (Federal Highway Administration 2012) in the gap analysis.

The six dimensions of CMM are the business processes, performance measurement, system and technologies, organization and workforce, collaboration, and culture. The identified business process gaps are related to the needs for institutionalization of MRM use for certain types of analysis, development and provision of methodology and guidance, allocation of funding and project time to meet the requirements for MRM, adoption of processes for model archiving and maintenance, and enhancement of contracting and procurement practices. The identified performance measurement gaps include variations in definitions of the methods used in the estimation of various performance metrics, data needs, types, and resolutions of the measures used in model calibration and validation. The gaps in systems and technology include the need for development and/or enhancement of methods and tools to support the integration and data conversion between different modeling levels, MRM tool enhancements, multimodal modeling, modeling of emerging technologies, assessment of various behavioral response levels to advanced technologies and strategies, simulation/model coupling for real-time management applications, and feedback loops for internally consistent cross-resolution traffic representation. The organization and workforce gaps involve the need for qualified staff to develop, calibrate, and peer review the developed models. There is a need to acquire experience and background through the recruitment, retention, and training of staff to support the MRM effort. Collaboration gaps include interagency and intra-agency collaboration. Culture in the context of MRM refers to the degree to which the benefits of implementing the tools are valued by the transportation agency. As indicated in this document, there is still a variation in the levels of adoption and interest of agencies in MRM.

The identified gaps as described in this document form the basis for the future activities of this project. The research team will conduct three case studies to support the provision of MRM guidance. The team proposed research activities for the case studies by mapping these activities to the identified gaps to ensure that the case studies will address the gaps. Although the team designed these case studies considering some of the identified gaps, other gaps do not lend themselves to examination by the case studies. Therefore, the team will address these other gaps as part of the developed guidance in this project.

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For figure 2, the original map is the copyright property of Google® Earth™ and can be accessed from https://www.google.com/earth. The map overlays showing regional, subregional, and corridor-level boundaries were developed as a part of this research project. The research team adapted figure 2 from Sloboden et al. 2012 (see References section).

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