Microsimulation: Department Assessment and Guidance

Final Report

Florida Department of Transportation (FDOT) Project

Contract Number: BDV29-977-61

Prepared for
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Prepared by
Florida International University

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DISCLAIMER

METRIC CONVERSION CHART

Approximate Conversions to SI* Units					**Approximate Conversions from SI Units**				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH					**LENGTH**				
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
AREA					**AREA**				
in^2	square inches	645.2	millimeters squared	mm^2	mm^2	millimeters squared	0.0016	square inches	in^2
ft^2	square feet	0.093	meters squared	m^2	m^2	meters squared	10.764	square feet	ft^2
yd^2	square yards	0.836	meters squared	m^2	m^2	meters squared	1.196	square yards	yd^2
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi^2	square miles	2.59	kilometers squared	km^2	km^2	kilometers squared	0.386	square miles	mi^2
VOLUME					**VOLUME**				
fl oz	fluid ounces	29.57	milliliters	ml	ml	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft^3	cubic feet	0.028	meters cubed	m^3	m^3	meters cubed	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.									
MASS					**MASS**				
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000 lb)	0.907	megagrams	Mg	Mg	megagrams	1.102	short tons (2000 lb)	T
TEMPERATURE (exact)					**TEMPERATURE (exact)**				
°F	Fahrenheit	(F-32)/1.8	Celsius	°C	°C	Celsius	1.8C+32	Fahrenheit	°F
*SI is the symbol for the International System of Measurement									

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EXECUTIVE SUMMARY

There is an increasing recognition of the need for additional guidance for utilizing simulation tools, considering the increasing complexity of the transportation system, the interactions of several factors in impacting system performance, and the increasing sophistication of strategies, technologies, and applications considered to increase system performance. This project provides guidance and directions to improve the Florida Department of Transportation (FDOT) microsimulation modeling practice, including the identification of the current and potential FDOT applications of transportation system simulation and associated needs; assessment of existing simulation manuals and guidance in Florida and providing recommendations for additions to the manual; assessment of the ability of available microsimulation platforms and applications to meet the simulation needs in Florida; provision of direction for the application of multiresolution as part of the modeling practice in Florida; exploration of the development of simulation modeling clearinghouse practices; and identification of FDOT training needs in relation to the use of transportation system simulation.

IDENTIFICATION OF FDOT NEEDS AND APPLICATIONS

The first task of the project involved conducting a Web-based survey of modelers from around the State of Florida using an online survey platform, in addition to on-line interviews with selected users. The goal was to identify how simulation modeling is applied and the needs of simulation modeling in Florida. Below is a summary of the findings.

Agency Processes and Resources

The simulation models in Florida are mainly developed by consultants. Not all consultants have the capability to develop simulation models, particularly for large networks. Some agencies have adopted detailed processes for the review. Others do not have such processes. When asked if the agency archives and maintains the simulation models after the end of the project, 57% of the respondents to the survey said they archive the model. The lack of budget affects the calibration quality and the number of alternatives that can be evaluated.

Guidance Utilization

Only 61% of the respondents said that they use formal guidelines or manuals in the development and calibration of models. Additional guidance is needed, including the provision of additional information related to data; provision of examples to model certain unique situations; extending the focus to include public transit, pedestrian, bicycle, and other modes of travel; recommending different approaches to modeling, depending on the analyzed alternatives; connected and automated vehicle modeling, and the provision of additional guidance for mesoscopic modeling and multiresolution modeling.

Analysis Types and Tools

Most modelers in Florida use either microscopic simulation or macroscopic analysis procedures and analytical (deterministic) tools like those based on the Highway Capacity Manual (HCM) procedures. In some cases, when using simulation, HCM analyses are performed for initial screening of the alternatives, and simulation is used later for more detailed analysis. However, the use of multiresolution modeling with dynamic traffic assignment (DTA) and/or mesoscopic simulations by the agencies is limited. In general, the selection of the tools is based on the judgment of the public agency and their consultant. Conditions that usually trigger the use of simulation are closely spaced intersection, high demand-to-capacity ratios in urban areas, backups between intersections and/or interchanges, complex system configuration, express lane use, etc. There is a need to make the business case for using simulation in processes that currently do not use simulation when it is needed. Proven cost effectiveness of the model level and tool utilization is critical.

Data Needs

FDOT is gathering data from different sources. There is a need to understand what data are needed and how the data can be used for different applications. There is a concern about data availability, particularly if data are required for multiple weeks and months and particularly for arterial streets. Origin-destination (O-D) data are also very important and difficult to get. In addition, there is a concern about the uncertainty in the quality and resolution of data from third-party vendors and sensors. There is also uncertainty about data quality in general and the need for guidance for data quality and data cleaning. There is need for the discussion of usable data and what constitutes useable data by type. A significant consideration is the inconsistency in the data, particularly when collected on different days.

Model Development and Calibration

A step-by-step guide for calibration would be helpful. There is a need for clear documentation of the calibration process conducted by the modeling team to allow a better review of the developed simulation model. Guidelines are needed on acceptable ranges for various driving behaviors parameters to use in the simulation tools in order to determine which field-measured metrics should be used under which circumstances. There is a need to identify the performance measures for use in reporting the results, including those that reflect the actual differences in system performance between alternatives and that can be understood by the decision makers. Regarding the measures currently used or needed based on the output of simulation models, the respondents reported that queue length, travel time, and level of service are the most widely used.. However, it appears that there has been limited of use of simulation to estimate additional measures like reliability, emission, fuel consumption, and safety. The idea of multiscenario analysis based on cluster analysis of traffic and event data seems to be attractive to Transportation Systems Management and Operations (TSM&O) and traffic engineering study staff. However, planning and design staff thinks that such analysis may add unacceptable additional costs. There is also an interest in modeling connected and automated vehicles (CAVs). O-D estimation using origin-destination matrix estimation (ODME) procedures is increasingly used. However, the results from ODME should not make the distribution very different from the seed matrix.

Training Needs

When asked about the training needs, about 44% of the survey respondents said that there is a need for a general training for simulation modeling. About 10% specified training on specific advanced topics like dynamic traffic assignment, automated output processing, application program interface, and modeling complex intersection and interchange designs. About 20% specified tool-specific training. It was reported that there is a large variation between the qualifications of different districts related to simulation analysis, although most of the modeling effort is done in general by consultants. There is a need for a training course to understand the concepts, and a general overview of the inputs and outputs. Most of the respondents indicated that training on basic concepts is critically needed more than training modelers on the details of creating and calibrating models. Some of the needed concepts can include when to use the simulation vs. analytical procedures like the HCM-based analysis, what happens when the model is not adequately calibrated, how to set temporal and spatial limits, and the importance of latent demands. Training should differentiate between information needed for consultants who create the model versus that needed for reviewers. There is a need to have a simulation overview course specific to TSM&O modeling. A course may also be needed to provide TSM&O staff with basic knowledge about the need and benefits of using simulation for TSM&O, including supporting performance impacts and return on investment estimation. Demand forecasting modelers may need a basic traffic flow module, and the microscopic simulation may need a basic demand forecasting module. All of these workshops can be a three-hour workshop. Data science has evolved and can be used to support modeling and forecasting. There may be a need for training on data and associated software such as Python. In addition, there is a need for a training on statistical analysis for traffic analysis and simulation. There is a need to build a user community similar to the model task force and regional user groups of demand forecasting models.

Future Year Demand Forecasting

The respondents believed that the demand forecasting models are not accurate enough to produce accurate traffic demands for simulation modeling, even when peak period models are used. The regional models are unconstrained by capacity. Thus, the model output volumes are higher than capacities, and the unmet demands cannot be correctly represented and simulated. In addition, the regional models are not validated at the turning movement volume level for the peak hour (peak 15 minutes are usually needed for the simulation). Demand forecasting models are often too general for the small focus area of the simulation. In addition, the traffic analysis zone's (TAZ's) definitions and their connections to the network links in the demand models are often too coarse and can lead to misleading results. Identifying the demand for the shoulder hours to the peak and for future years, including peak spreading, is challenging. One respondent recommended adopting the National Cooperative Highway Research Program (NCHRP) NCHRP 765 demand forecasting procedure across the state for future demand forecasting. It appears that the quality of the demand models varies by region and location within the region. The demand matrix from the forecasting model, if of a good quality, can used as a seed matrix to ODME procedures. The respondents appear to use different methods to forecast future year demands, including using the demand forecasting models, growth rates (based on counts, demand model growths, and a combination of the two), self-developed Excel spreadsheets possibly combined with ODME process, the Florida Project Forecasting Handbook procedure, using tools like TURNS and Matrix Variator (this tool is used for peak spreading), DTA, and NCHRP 765 procedure.

ASSESSMENT AND EXTENSION OF AVAILABLE GUIDANCE

The FDOT's Traffic Analysis Handbook provides guidance for use of traffic analysis tools in FDOT projects. The Handbook addresses analytical tools such as HCM-based tools, highway safety manual (HSM)-based tools as well as microscopic simulation (microsimulation) tools. This project focuses on needed traffic simulation guidance not covered or has limited coverage in the Traffic Analysis Handbook and provided information that can be used as a basis for new sections in the manual including:

- **Representative Day and Multiscenario Analysis**: This item focuses on how to select a representative day for the analysis and single analysis vs. multiscenario analysis.

- **Setting Calibration Targets:** This item addresses the simulation calibration targets provided by the FDOT with the targets provided by other state DOTs and national guidance.

- **Estimation of Non-Traditional Measures**: This item discusses estimating measures such as safety performance metrics, sustainability metrics, and travel time reliability metrics based on simulation results.

- **Post-Project Validation:** This item provides recommendations regarding post-project validation for checking that the calibrated model is able to predict the performance of the system after implementing the project improvement.

- **Calibration of Bottleneck Attributes:** This item presents additional information regarding calibrating the performance of traffic bottlenecks, which is one of the most critical aspects of traffic simulation.

- **Automated Data Sources:** This item considers existing and emerging data sources that can be used to support simulation modeling and its strengths and limitations. The discussed data sources include point detectors, Bluetooth and Wi-Fi readers, private sector travel time data, private sector O-D data, high resolution controller data, connected vehicle (CV) and automated vehicle (AV) data, vehicle trajectories, and event data.

- **Data Quality Assurance:** This item discusses the importance of data quality assurance and the procedures used to assure data quality.

- **Traffic Assignment:** This item discusses traffic assignment with focus on dynamic traffic assignment, including assignment components, assignment types, generalized cost function formulation, convergence, demand estimation, and zone and connector disaggregation.

- **Multiresolution Modeling:** This item addresses conducting multiresolution analysis, including project planning and scoping, performance measure identification, data requirements and availability, model development, and ensuring MRM consistency

- **Modeling of Connected and Automated Vehicles**: This item addressed connected and automated vehicles (CAV), CAV modeling framework, identification of the technical approach, uncertainties associated with CAV, performance measure identification, data requirements and availability.

After providing recommendations regarding additional guidance on the topics in the above list, this project researched two of the topics in the list in more details. First, this study compared the results from using calibration targets that vary depending on the day-to-day variations in the traffic measures of a segment as proposed in the updated Federal Highway Administration (FHWA) calibration methodology with the fixed targets recommended in the FDOT and other state DOT guidelines. The results indicated that the examined state calibration target is comparable to the calculated targets calculated based on the FHWA method when the standard deviation of the link volume is relatively low (below 85 vehicles per 15 minutes). However, the states' calibration target becomes more conservative when the standard deviation is higher, and this difference increases with the increase in the standard deviation. The study also found that the fixed travel time target appears to be less restrictive compared to the targets calculated using the FHWA methodology for freeway links with relatively short travel times and lower standard deviations, as in the case study. However, the conclusion could be different for segments with higher travel times and lower standard deviations. The analysis in this study indicates that assuming that the event-free days belong to one pattern can result in high standard deviations of the MOEs of some of the links, resulting in large acceptable deviations between the simulation results and real-world measurements. Thus, further clustering of the event-free days into more than one pattern is recommended when applying the FHWA methodology, when the standard deviations of the performance measures are high. The study results confirm that such clustering can produce tighter acceptance thresholds. Additional guidance is needed regarding the number of clusters to use in identifying the operational scenarios. The more are the number of clusters, the lower is the standard deviation and thus the tighter are the acceptance thresholds.

The second topic in the list that this study investigated was to answer questions regarding the selection of the best day(s) for traffic analysis and identified methods for this selection using cluster analysis. The study showed that the use of input measures for clustering that are segregated in space (by road segments) and in time (by interval of the peak period) produces better clustering results compared to the use of input measures that are aggregated in time and/or space. The study also compared the quality of the results with using different clustering algorithms and number of clusters. The results presented in this study also clearly show that the use of an average day of the year or an average day of the peak season is not a good approach for selecting a day for the analysis. In addition to the fact that averaging volume and travel time data results in synthetic days that do not occur in the real world, such averaging results in diluted congestion levels. The analysis of the case study in this research indicates that a large percentage of the days have significantly higher congestion levels than the congestion level of the average days. Thus, the use of the average day for making highway design decisions for example can result in the under-design of the facility.

ASSESSMENT OF AVAILABLE SIMULATION PLATFORMS

This project also evaluated traffic analysis platforms that could potentially meet FDOT needs. The task identified a set of capabilities and use these capabilities to compare the analysis tools. The comparison among the traffic analysis tools in this document utilized the official manuals, user guides, and other documents. The main utilized documents are the Synchro Studio 11 User Guide (Cubic ITS Inc., 2019), PTV Vissim 2021 User Manual (PTV AG, 2021), Vissim's RBC User Manual (PTV AG, 2020), Highway Capacity Software (HCS) Users Guide (McTrans, 2019), North Carolina Department of Transportation (NCDOT) guidelines for TransModeler (NCDOT, 2016), and TransModeler Program Help documents. However, the study also evaluated the simulation by the investigated tool of specific features utilizing model runs of the tools. These specific features are lane width, grade, and truck presence. The following are the findings from the comparison.

1. The HCM/HCS procedures can be used to analyze local intersections and segments in addition to linear freeway and arterial segments. In addition, Synchro and SimTraffic documentation stated that these tools can model grid street networks. Synchro and SimTraffic cannot model freeway segments. The HCM/HCS has procedures to model rural two-lane and four-lane highways. The HCM/HCS, Synchro, and SimTraffic cannot model an integrated network of freeways and arterial streets. A main advantage of Vissim and TransModeler is their ability to model a network of model freeways and arterials and their interactions. TransModeler can also model two-way two-lane rural highways.

2. Traditionally, the HCM/HCS procedures for isolated intersections and segments have been developed to analyze the peak 15 minutes within the peak period. However, the freeway and arterial facility procedures developed later allow for the modeling of multiple periods, although the length of the period is still generally fixed at 15 minutes. Synchro, SimTraffic, TransModeler, and Vissim are flexible in simulating multiple periods with varying lengths.

3. The HCM/HCS, Synchro, and SimTraffic require the inputting of the turning movement volumes or percentages of the approach volume at each intersection and ramp. The users of Synchro and SimTraffic can also specify "local pairing" of volumes between a pair of upstream and downstream intersections. An advantage of Vissim and TransModeler is the ability to model the traffic from their origins to their destinations, although both allow for the inputting of turning movement counts if the user prefers. Both Vissim and TransModeler can accommodate dynamic traffic assignment. Vissim allows several other advanced routing methods that can be used to ensure better replication of the routes from

origins and destinations if the dynamic traffic assignment option in the tool is not used. These routes can be identified based on higher level assignment models such as those incorporated in Vissim.

4. Synchro and the HCM/HCS apply factors to reduce the saturation flow rates and capacities based on the proportion of trucks in the traffic stream. However, these factors assume one type of truck with specific power-to-weight ratio for arterial analysis and two types of trucks with specific power-to-weight ratios for the HCM freeway analysis. SimTraffic can model four types of trucks. The user can vary the proportion, acceleration, and dimensions of these vehicles. TransModeler can model single unit trucks and trailer trucks, and the user can specify the mean, standard deviation, and distribution of the mass and power parameters for each vehicle class. Vissim can specify the distribution of the length, weight, power, and acceleration/deceleration characteristics of vehicle classes (including heavy vehicles) with no limitations on the number of the truck types in the program. If the trucks are expected to have significant impacts on system performance, the user needs to identify the truck type mix in the traffic stream, determine if the analysis tool allows for the inputting of this mix, and then examination of the impact on the performance of the truck mix based on whether the simulation results are logical.

5. Synchro/SimTraffic and the HCM/HCS consider the impacts of upstream bus stops in the close proximity to the intersection on the saturation flow rate. However, they do not explicitly model bus operations and the detailed interaction of individual buses with the traffic. Vissim and TransModeler can model the different types of buses and trains, including routes, bus stops, and dwell times at bus stops. These simulation tools can estimate the performance of the public transit routes.

6. The user can specify non-motorized traffic in HCM/HCS and Synchro/SimTraffic to be used in estimating the impacts of the conflicts with the turning vehicles on the saturation flow rates of the turning movements, as well as to estimate the changes in the actuated signal timing due to pedestrian phase activation. However, non-motorized traffic, including individual pedestrians or bicycles, are not explicitly modeled to be able to determine the stochasticity of their operations or to derive the performance measures associated with these operations, as can be done with Vissim and VisWalk. Although TransModeler can model the effect of pedestrian on vehicular traffic capacity, it does not produce pedestrian performance measures.

7. Vissim implements the Wiedemann car-following model, which is a recognized car-following model. TransModeler allows using the GM model, Gipps model, Wiedemann models, and Intelligent Driver model, which is a nice research capability. The vendor can provide guidance as to when these models should be used in practice.

8. The HCM/HCS and Synchro as macroscopic tools do not explicitly model lane changing, although the HCM implicitly considers the impacts of lane changing in their merge, diverge, and weaving freeway segments. Both Vissim and TransModeler have detailed mandatory lane change (MLC) and discretionary lane change (DLC) with multiple parameters that can be fine-tuned. SimTraffic only allows MLC (no DLC), and the lane changing model is simplified with only two parameters.

9. Although the HCM/HCS and Synchro procedures can consider the impact of congestion and spillbacks, the operations under oversaturated conditions and the spatial and temporal influences of congestion are base modeled using microscopic simulation models. These models have the ability to model the queue growth from one interval to the next. They can also model oversaturation and spillover from the turn bays to adjacent lanes, and from one segment to the next. Additional advantages of simulation models are their ability to consider the impact interactions of upstream and downstream bottlenecks and downstream hidden bottlenecks that can appear after solving the upstream bottlenecks.

10. Synchro and HCM/HCS procedures use average desired speeds for a link and do not consider in detail the variations in individual vehicle speeds on performance, although the HCM arterial street facility procedure has a platoon dispersion algorithm that considers the change in the platoons as they progress from upstream to downstream signals. TransModeler, Vissim, and SimTraffic allows for the changing of speed by link and vehicle/driver types. In TransModeler, users can input speed limits for different road classes (freeway, rural highway, expressway, weaving, system ramp, collector-distributor, ramp, minor arterial, major arterial, minor collector, major collector, local street, access road, trail road, roundabout, tunnel, rail, waterway, freeway-piecewise linear and freeway-Van Aerde), each of which may follow six desired speed distributions (standard, school zone, work zone, freeway, major and minor arterial). TransModeler and Vissim have more flexibility in assigning speeds to more vehicle/driver types. In addition, it seems that SimTraffic does not consider the stochasticity of speed for each vehicle type.

11. Advanced operations, active management, demand management, and pricing strategies are best analyzed using advanced simulation tools like Vissim and TransModeler. These programs have API facilities that can integrate codes to emulate these strategies with the simulation models. Vissim has the ability to have co-simulation that involves software-in-the-loop, hardware-in-the-loop (e.g., signal controller in the loop), human-in-the-loop, and/or vehicle-in-the-loop (including human-driven and connected and automated vehicles). TransModeler may have at least some of these capabilities, but this has to be investigated. SimTraffic allows interfaces with controller-in-the-loop but does not allow the modeling of advanced strategies or additional co-simulation options.

12. The HCM/HCS has a limit on the number of approaches and lane groups that can be analyzed a (maximum of four legs and a maximum of three lane groups per approach). Other examined analysis tools do not have this limitation. Lane width impacts capacity in the HCM/HCS, Synchro, and TransModeler. The lane width does not affect capacity in the Vissim and thus this impact has to be approximated by manipulating other input parameters. It is not clear if SimTraffic can simulate the impact of lane width. The impact of the reduction in the lanes on the departing (receiving) approach on vehicular traffic capacity cannot be accurately modeled using analytical/deterministic tools; they can best be modeled using simulation models.

13. The imbalance in lane utilization can affect the performance of the signalized intersection. The HCS/HCM and Synchro have default values for lane utilization. Vissim and TransModeler assign the traffic to lanes based on their downstream turns. In addition, TransModeler can use the lane utilization factor from the HCM and input a factor to bias

the traffic towards specific lane(s), which is a nice feature to have if it works correctly. It is not clear of how well SimTraffic assigns traffic to lanes. If the user inputs the upstream-downstream demand pairs between upstream and downstream intersections, one may think that the model may be able to assign the vehicles to lanes considering this pairing. However, this is not certain and needs to be tested.

14. Upgrades and downgrades impact capacity in the HCM/HCS, Synchro, Vissim, and TransModeler. The impact of the change in capacity with different truck proportions and compositions in different tools should be examined.

15. Left- and right-turn radii are used as inputs to HCS/HCM and Synchro, and these values affect the capacities of the associated movements. All three microsimulation models use turn speeds rather than turn radii to impact capacity. TransModeler also allows for the inputting of turn radii. The user should examine how the turning speeds in each of the microscopic simulation tools impact capacity.

16. The HCM/HCS arterial street procedure applies a macroscopic platoon dispersion model to estimate the arrival on green at the downstream signal based on the link speed, offset, distance between the upstream signal timing, and the implemented platoon dispersion model. Synchro determines the platoon arrival on green based on the link speed and the distance between the upstream signal timing. However, it does not implement a platoon dispersion model. Coordination and offset impacts are modeled in detail in Vissim, TransModeler, and SimTraffic as the individual vehicles progress from the upstream signal to the downstream signal.

17. The modeling of shared lanes is challenging. Synchro and HCM/HCS have models for estimating the capacities of these lanes but require the user to input the number of vehicles that use the shared lane when there is an adjacent exclusive lane that can be used by the vehicles. Microscopic simulation models assign the vehicles to the shared lanes based on downstream/upstream lane changing. The lane assignment and the resulting capacity estimates need to be further examined by the users. SimTraffic does not seem to consider the impact of a shared lane.

18. In situations where midblock constraints and frictions such as the case with parking activities, work zones, incidents, and parking impact traffic, models like Vissim and TransModeler are recommended. TransModeler has a detailed built-in on-street parking model.

19. HCM/HCS and Synchro have detailed permissive left-turn models that can provide good estimates of capacity. The microscopic simulation models allow for better consideration of upstream and downstream intersections, the platooning of opposing traffic that generates different gaps in traffic than random arrivals, the vehicle type (including heavy vehicles), impacts of upstream and downstream congestion, and the stochasticity of drivers' behaviors. It is recommended that when using simulation models to confirm the resulting capacity versus those obtained from the HCM, the difference for basic traffic conditions is explained in detail.

20. HCM/HCS requires the inputting of the right-turn-on-red (RTOR) capacity, which is difficult to estimate. Synchro has a macroscopic model that can provide estimates of RTOR capacity. The microscopic simulation models have better consideration of upstream and downstream intersections, the platooning of opposing traffic that generates different gaps in traffic compared to random arrivals, the vehicle type (including heavy vehicles), and the stochasticity of drivers' behaviors.

21. All reviewed tools have actuated control models that allow the inputting of complex actuated controller modeling parameters. Microscopic simulation modeling has better consideration of the local arrivals' patterns, stochasticity, detection configuration, and controller setting. Vissim allows controller software-in-the-loop and hardware-in-the-loop, which allows for even more realistic modeling of actuated controllers.

22. Advanced control strategies like emergency vehicle preemption, transit signal priority, and freight priority can be modeled in Vissim and TransModeler, but not in the evaluated analytical tools and SimTraffic. TransModeler can model the preemption and priority calls, while Vissim can model ten preemption and priority strategies with different levels of priorities.

23. Vissim and TransModeler are more flexible in inputting various configurations of two-way stop-controlled intersections (TWSC). However, the user needs to examine the operations of the simulated intersections to ensure that it replicates real-world priority rules. The resulting capacity from these simulation models can also be compared with HCS procedures to ensure that they produce the same capacities for the same conditions if real-world capacity data are not available. TransModeler appears to have the ability to automatically account for lane width. SimTraffic simulation of unsignalized intersections should be carefully examined since this program was originally developed as a signalized intersection model.

24. All tools allow for the inputting of upgrades and downgrades. The user should recognize that the HCM procedures assume certain types of trucks and may not produce accurate impacts if the truck composition is different. Vissim, TransModeler, and SimTraffic are more flexible in specifying the truck composition and thus the impacts on grades. However, the results from these models need to be verified and calibrated.

25. Vissim and TransModeler are more flexible in inputting various configurations of TWSC. However, the user needs to examine the operations of the simulated intersections to ensure that it replicates the real-world priority rules.

26. HCM 2016, Vissim, and TransModeler allows two-stage gap acceptance at TWSC. Synchro can model this feature only when requesting the HCM 2016 analysis option. SimTraffic does not model this feature.

27. The HCS/HCM procedure allows for the inputting of an average free flow speed by segment. On the other hand, Vissim and TransModeler use free flow speeds that vary by vehicle type with a stochastic variation of these speeds resulting in different free flow speeds for individual vehicles in the simulation.

28. The HCS/HCM procedure considers the impacts of a number of features, including lane width, lateral clearance, and the proximity of other interchanges. The proximity of other interchanges is assessed based on the microscopic interactions of vehicles in Vissim and TransModeler. TransModeler considers the impact of lane width and shoulder width on speed. However, these impacts have to be input manually by the user in Vissim.

29. The HCM includes a detailed procedure based on a research effort that considers the specific characteristics of managed lanes (ML) and the separation of the ML and general purpose lanes (GPL). This is not considered in simulation models. It is useful to incorporate the impacts derived based on the HCM ML procedures, particularly the impact of the ML separation type, in conjunction with the modeling of ML in the simulation tools.

30. If the user measures the free flow speed and capacity in the field, then the simulation model can be calibrated to produce these values. If this is not possible (for example, in the case of future geometry), the user should consider this factor in estimating capacity and use the results to fine-tune the car-following parameters in the models to produce the capacity.

31. The HCM includes speed and capacity adjustment factors for the impacts of adverse weather events, incidents, and work zone conditions. The recommendation to the user is to apply the estimated capacities and free flow speed obtained from the HCM procedures to inform the simulation analysis. TransModeler has a lane blockage model for use in assessing incident and work zone impacts. Although not explicitly modeled, the impacts of these lane blockages can be emulated in Vissim.

32. The HCM/HCS has procedures to analyze weaving segments that were derived based on empirical data. The data were collected for specific configurations, and the procedures do not consider the upstream and downstream interchanges, intersections, and bottlenecks on the operation. Simulation models are flexible in modeling various weaving configurations and impacts of adjacent bottlenecks and junctions. However, the modeler needs to be very careful in ensuring that the model is accurately simulating the weaving segment. The FDOT weaving segment simulation procedure presented in the 2021 Traffic Analysis Handbook should be used. The modelers need to examine the ability of TransModeler and Vissim to apply the FDOT procedure mentioned above. Such complex weaving segments cannot be analyzed using the HCM/HCS procedure.

33. The HCM has procedures to analyze the merge and diverge areas within 1,500 ft of the on-ramps and off-ramps. Simulation models are flexible in modeling these operations and the impacts of adjacent bottlenecks, junctions, and congestion. However, the modeler needs to be very careful in ensuring that the model is accurately simulating the lane changing behaviors in these areas. The user should calibrate the model based on real-world data and HCM procedure results. The availability of trajectory data from connected vehicles and advanced sensor technologies will assist with better calibration of the models.

34. The latest version of the HCM allows for the simulation of cooperative adaptive cruise control (CACC), platooning, and dynamic merge control on freeway segments. The parameters of the modeling were derived based on Vissim simulation results, combined with observed CAV driving behavior in a prior test. The procedures do not consider non-

connected automated vehicles and the specific impacts of managed lane driving. Vissim and TransModeler introduced new driving behaviors that can be used to model the longitudinal movements, lateral movements, and combinations of these movements. It appears that the default parameters were derived based on limited data, and further research is needed to confirm and extend these models. There are a large number of mobility, safety, and environmental impact applications and features of connected, automated, and cooperative driving automation other than the ones modeled by the HCM/HCS procedures and the built-in procedures in the traffic simulation tools. These features can be modeled using the API facilities in the simulation tools and various software-in-the-loop and hardware-in-the-loop configurations.

35. The desired speed is an important parameter that impacts simulation results. Vissim uses narrower default speed distributions for the CAV. On the other hand, TransModeler removes the stochasticity of the desired speed only from Level 3 automation.

36. All assessed tools allow for the modeling of different market penetrations of CAVs. TransModeler and Vissim have the advantage of the ability to include mixtures of CAVs with different characteristics and levels of automation and connectivity that consider the expected changes in the market penetrations of these technologies over time. All tools will allow for the modeling of exclusive lanes for CAV.

37. The user needs to understand the limitations of the analysis in each tool. For example, for CAV, the HCM limits the weaving volume ratio to total demand volume from 0.2 to 0.4.

38. Among the three compared simulation tools in this study, only Vissim and TransModeler have dynamic traffic assignment and multiresolution modeling capabilities. These capabilities will be compared in Task 4 of this project.

Next, using tool run results and based on model runs, this study examined the ability of HCM-based deterministic analysis tools and microscopic simulation tools to assess the impacts of lane width and upgrades with different truck percentages on the capacity of basic freeway segments, signalized intersections, and unsignalized intersections. The study also investigated the impacts of changing the parameters of microscopic simulation models on the assessment of the impacts of these design features. The results indicated that the current versions of these tools do not consistently consider the impact of the investigated design features on highway capacity. The results indicate different changes in capacity due to the changes in geometry and truck percentages. The results from some tools do not show impacts of specific geometry features without changing the default calibration parameters for the modeled segments. In another case, a tool was able to model the impacts of a feature on capacity only on interrupted facilities or only for uninterrupted facilities.

PROVIDING DIRECTION ON THE APPLICATION OF MULTIRESOLUTION MODELING

This project also provides direction on the application of MRM. This effort will build on recent national effort funded by the FHWA that provided a review of the state of practice, guidance, and case studies for the use of MRM (Hadi et al., 2022a, 2022b; Zhou et al., 2021). The principal investigator (PI) for this project was also a PI for the FHWA project. It is recommended that the FDOT team that is developing and maintaining the FDOT Traffic Analysis Handbook (TAH) review the FHWA project deliverables and incorporate information from the deliverables in the FDOT TAH. This FDOT research project provides the following:

- Recommend guidance based on a recently completed FHWA project on MRM
- Develop methods for integrating crowdsourced data from a third-party data vendor in the process of estimating the origin-destination matrix estimation (ODME) process required for the MRM for the modeled scenario(s)
- Assess the use of crowdsourced data platform obtained from third-party vendors to estimate segment level daily and hourly volumes.

MRM GUIDANCE BASED ON RECENTLY COMPLETED PROJECT

The FHWA and the Traffic Analysis and Simulation Pooled Fund Study sponsored a research project on multiresolution modeling (MRM). The project provides guidance that summarizes MRM terminology and definitions, a methodology for MRM analysis, and three case studies of applying MRM (Hadi et al., 2022a, 2022b). The MRM methodology in the guide extends the methodology provided for simulation analysis in FHWA's Traffic Analysis Toolbox Volume Ⅲ: Guidelines for Applying Traffic Microsimulation Modeling Software (Wunderlich et al., 2019). The following are the steps that are addressed in the guidance. These steps should be reviewed by the FDOT Traffic Analysis Handbook development and maintenance team for use in updating the Handbook.

- **MRM Scoping and Planning:** This includes making decisions regarding the MRM utilization and approach based on the needs and objectives. It involves specifying and defining performance measures to be estimated using different resolutions of MRM, determining additional data requirements for the use of MRM, identifying the geographic and temporal scope for each resolution, identifying the analysis approach for each resolution level, and resource allocation

- **Data Collection and Analysis:** This step considers that MRM requires additional data collection and processing activities. It should be mentioned that the main objective of the MRM task conducted as part of the FDOT project is to investigate the use of data from multiple sources to support the MRM.

- **Base Model Development and Error Checking:** The methodology then addresses the additional effort required for MRM model development, including interfacing MRM tools, disaggregating zones, and modifying connectors, O-D demand estimation, signal control modeling, advanced technology modeling, and multiscenario analysis.

- **Model Calibration and Convergence:** This involves the steps required for MRM calibration. These steps include bottleneck identification, traffic flow model calibration for different resolutions, and travel demand calibration.

- **Alternatives Analysis:** This step includes accounting for model stochasticity, estimating future-year demands, estimating, and optimizing signal timing, and conducting sensitivity analysis to account for uncertainty in model inputs.

The guidance also provides recommendations to improve the organizational and technical capabilities of the agencies to increase their MRM analysis capabilities in various dimensions, including the business processes, performance estimation, data collection and management, development of standard operating guidance, tool utilization, workforce development, collaboration, and culture.

The FHWA guidance referenced previous FDOT projects by Hadi et al. that developed MRM tool assessment criteria to enable the comparison of various modeling tools to ensure they meet the needs of a specific project (Hadi et al., 2012, 2016). The criteria for tool assessment cover general hardware and software, shortest path and path choice modeling, traffic flow modeling, network geometry modeling, network demand modeling, transit modeling, and calibration/validation and convergence assurance support. Additional criteria were developed for specific applications such as managed lane, work zone, and advanced traffic management strategy modeling.

A critical aspect of MRM is to understand how different performance measures are calculated by different tools at different resolution levels. Measures such as travel time, delays, stops, queues, and density have the same name in different tools but are defined and calculated differently. An important aspect that was introduced and emphasized in the FHWA guidance is to ensure consistency between different levels of modeling by applying feedback from higher resolution models to lower resolution models.

UTILIZING CROWDSOURCED DATA IN ORIGIN-DESTINATION MATRIX ESTIMATION (ODME) PROCESS

Origin-destination demand estimation is a vital part of MRM. The resulting traffic O-D demand matrices are used as inputs to static and dynamic traffic assignment models that are important components of the MRM. Often, in current practices, the traffic O-D demands used as inputs to the traffic assignment are extracted for a subnetwork from the larger networks modeled in existing regional travel demand models. However, modelers are often challenged with the inadequate quality of the O-D demand matrices obtained from demand forecasting models, which result in large errors in the link counts resulting from the assignment compared to real-world counts (Hadi et al. 2022). This implies the need for further refinement of the ODME procedures and the use of additional data sources as inputs to these procedures to allow these models to produce results that are acceptable for simulation modeling. In many cases, modelers have used ODME procedures that utilize a combination of traffic counts and initial O-D demand matrices obtained from the demand models to obtain better estimations of the O-D demand matrices. Still, questions remain about the quality of the O-D matrices resulting from the ODME procedures. This study explored the possibility of including crowdsourced data sources into the ODME process and evaluated the quality of the resulting O-D matrices.

This study explored twelve variations of the O-D matrix estimation procedure with and without the use of crowdsourced data.. The ODME procedure used in this study is an assignment-based procedure which utilized the static traffic assignment option in this study. A comparative analysis is performed between all of the investigated methods to identify the best way to develop an O-D matrix.

Based on the analysis presented in this study, Method 3(b) produced the best results considering that it produced low deviations from the real-world counts and the O-D matrix obtained based on Streetlight data. It also produced comparable deviations from the regional demand model O-D matrix to the deviations obtained with the other methods. The steps of Method 3(b) are listed below. Please, note that the relative weights in Steps 1 and 3 can be changed by the user depending in their confidence in the accuracy of different input variables.

- Step 1: an ODME procedure is run using the count data and O-D matrix obtained from the demand forecasting model with a relative weight of ten on the O-D matrix. Crowdsource data is not used here since crowdsource data is not expected to produce good estimates of the demands due to the small sample sizes.
- Step 2: the trip generated according to the O-D matrix derived in Step 1 are redistributed based on the SL Index proportions obtained from the acquired crowdsource data. The estimation of the proportions of the trips going to each destination based on the SL index proportions are expected to be more accurate than the proportions based on the demand forecasting models since they are based on real-world measurements
- Step 3: A second ODME process is conducted with an initial O-D matrix obtained from Step 2 with a relative weight of 1 on the O-D matrix to obtain closer results of the resulting assigned volumes to real-world traffic counts.

USING CROWDSOURCED DATA FOR SEGMENT-LEVEL VOLUME COUNT ESTIMATION

In addition to providing data that can be used for O-D matrix estimation, crowdsourced data have been proposed to provide estimates of daily and hourly traffic volume counts. Such estimates can be used to provide support to analysis, simulation, and MRM, as volume count data are expensive to collect and in many cases, counts are available only for short periods of time and may not cover all links in the network. This study investigated utilizing crowdsourced data in combination with the real-world data collected from permanent detectors at specific locations to estimate the link volumes and discusses the assessment, the accuracy, and the transferability of using the data for link volume estimation.

The results presented in this chapter indicate that there are significant discrepancies between the AADT and MADT estimated based on the SL Expanded volume data and the permanent count station (PCS) data used as ground truth data for the two locations. Large errors were also found when estimating the seasonal factors based on the SL data. Considering the results above, this study investigated and refined the volume estimation by developing regression models that relate the crowdsource data to the ground truth PCS data. These models were then investigated for use to expand the crowdsource data. The results from the regression analysis indicate that statistically significant relationships could be obtained between the PCS daily counts and crowdsource daily data. The results indicate that the development of regression models data has the potential of providing acceptable results for daily volume estimation, particularly for higher volume segments. However, it should be remembered that the testing in this study is done using PCS Count and crowdsource data from the same location from which the data is collect from for the regression. For the models to be useful, they need to be tested to estimate the volumes for locations other than the locations of the PCS station used in the regression. Such testing should be done in a future study. It is evident that all regression models developed in this study for hourly volumes, produced large errors in hourly volume estimation.

EXPLORING THE DEVELOPMENT OF MICROSIMULATION CLEARINGHOUSE PRACTICES

This study identified the needs of the FDOT in traffic simulation training. Training is needed to build a robust workforce within the FDOT and its public sector partners and consultant, which is needed to maintain and advance traffic analysis and simulation capabilities. Currently, there is a limited FDOT-sponsored training for microsimulation and multiresolution modeling training. A recent FHWA study has developed a capability maturity framework (CMF) for transportation agencies to assess their traffic analysis and simulation capabilities and to identify the potential steps for the agency to take to advance to the next level of capability based on the needs and priorities of the agency (Hadi et al. forthcoming). The framework categorized the capabilities in eight major dimensions and 25 subdimensions related to these eight dimensions. The framework allows the ranking of the capability of the agency in one of four levels of maturity for each dimension. These dimensions and subdimensions of the capabilities identified in the above-mentioned project were used in this study as a basis for identifying the training needs to advance the capabilities.

The followings workshops were identified in this study to address the training needs:

- Traffic Simulation for Decision Makers
- Traffic Simulation Project Scoping and Procurement
- Supporting Data for Traffic Simulation
- Traffic Flow Theory and Characteristics
- Basic Traffic Simulation Concepts and Applications
- Advanced Traffic Simulation Concepts and Development
- Modeling Advanced Vehicle Technologies
- Dynamic Traffic Assignment
- Simulation Model Verification, Calibration and Validation
- Reporting and Utilization of Traffic Simulation Results
- Simulation Model Review/Quality Checking
- Statistical Analysis for Traffic Simulation

The study provided the following for each of the workshop.

- Workshop description
- Content

- Addressed needs
- Supported dimensions of the capability maturity
- Expected outcomes
- Attendees' levels
- Estimated duration
- Constraints

EXPLORING THE DEVELOPMENT OF MICROSIMULATION CLEARINGHOUSE PRACTICES

This project provided recommendations for an analysis, modeling, and simulation (AMS) project clearinghouse for archiving and maintaining data, performance measures, analysis files, and documents. This study strongly recommends considering the use of the Mobility Data Integration Space (MDIS) that is being developed by the FDOT as a candidate for use as the platform to support the data use and exchange associated with AMS projects. Additional effort would be needed by the MDIS team to ensure that the use of the system for data capture, archiving, and provision will meet the needs of the AMS.

It is recommended that the FDOT form a stakeholder group that involves public and private sector simulation model users in Florida, the MDIS team, and the FDOT modeling and data leadership in early discussion to establish the AMS data clearinghouse with the potential use of MDIS of this project. It will also be very useful to identify at least one case study to demonstrate the feasibility of archiving AMS and model data and to identify any limitations and issues with the process.

This project recommended that the project team of a traffic simulation project develops a data management plan (DMP) according to the needs and requirements of the established framework. The DMP will describe how the data and models of the analysis project will be generated, collected, managed, stored, protected, re-used, archived, and shared. The DMP and the clearinghouse will include metadata in a standard format that describes how the data will be managed and archived and outlines the access policies and methods, including any restrictions on the access, and re-use policies, including any restrictions on the use of the data and model outputs.

If the goal of the clearinghouse is just allowing the users to download files and data associated with specific segments or zones, then the clearinghouse will require just the use of standard metadata and linking attribute. However, if a decision is made at the initial or later versions of the clearinghouse to use of input and output variables from AMS projects as attributes of data elements in the dataset such as links and subareas, standard specifications will be needed to define these variables such as those of MDIS, Florida Standard Urban Transportation Modeling Structure (FSUTMS), the General Modeling Network Specification (GMNS), or a combination. A common network specification will make it easier to share networks and will thus make it easier to share data and models. Even if this GMNS specification is not used by the FDOT, it is recommended that the FDOT review the GMNS for potential use considering the advancement in MDIS development, AMS data clearinghouse, and multiresolution modeling and the associated need for modeling data exchange in Florida.

One of the important issues that will impact the effectiveness of the clearinghouse recommended in this study is the issue that major new releases of the most existing tools are not backward compatible with the previous versions. This means a version created using an older version of a tool may not run with the new version of the model. It is recommended that the FDOT discusses with the tool vendors approaches to address this issue.

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CHAPTER 1: INTRODUCTION

BACKGROUND

The Florida Department of Transportation's (FDOT) Traffic Analysis Handbook provides guidance for the use of traffic analysis tools in FDOT projects, including corridor studies, interchange access requests (IARs), and project development and environmental studies (PD&E studies). The handbook also addresses analytical tools such as Highway Capacity Manual (HCM)-based tools, Highway Safety Manual (HSM)-based tools, and microscopic simulation (microsimulation) tools. The FDOT PD&E manual also has a chapter on the utilization of analysis tools in PD&E studies. Other states such as Wisconsin, Iowa, and Virginia have also developed guidance for the utilization of simulation modeling. The Federal Highway Administration (FHWA) traffic analysis toolbox documents also provide valuable information on the use of traffic analysis tools, including simulation and dynamic traffic assignment (DTA) tools. These documents are valuable for transportation system modeling and can be found on the FHWA website (http://ops.fhwa.dot.gov/trafficanalysistools). However, there is an increasing recognition of the need for more detailed and specific guidance for utilizing simulation tools, considering the increasing complexity of the transportation system, the interactions of several factors in impacting system performance, and the increasing sophistication of strategies, technologies, and applications considered to increase system performance.

The "Microsimulation: Department Assessment and Guidance" research project built on the existing state and national efforts to improve FDOT's microsimulation modeling practice through guidance and training. The project provides direction and updated guidance on using simulation to support the various business processes of FDOT and partner agencies, considering the increased complexity and congestion of the transportation system and the adoption of advanced vehicle and infrastructure-based technologies and applications. Results from this research will lead to the development and utilization of more effective and accelerated understanding, review, and delivery of FDOT-guided simulation projects and will promote consistency of practice, enhanced training, and clearly defined expectations for microsimulation projects.

GOAL AND OBJECTIVES

The research goal is to provide guidance and direction to improve FDOT's microsimulation modeling practice. The specific objectives of this project were:

- Identification of the current and potential FDOT applications of transportation system simulation and associated needs
- Assessment of existing simulation manuals and guidance in Florida and provide recommendations for additions to the manual
- Assessment of the ability of available microsimulation platforms and applications to meet the simulation needs in Florida
- Provision of direction for the application of multiresolution as part of the modeling practice in Florida
- Exploration of the development of simulation modeling clearinghouse practices

- Identification of the department training needs in relation to the use of transportation system simulation.

DOCUMENT ORGANIZATION

Chapter 2 of this document reports on the results of Task 1 of the project. This task involves conducting a web-based survey of modelers from around the State of Florida using the Qualtrics On-line Survey platform. The goal was to identify how simulation modeling is applied and the needs of simulation modeling in Florida.

The FDOT's Traffic Analysis Handbook provides guidance for use of traffic analyses tools in FDOT projects. The Handbook addresses analytical tools such as HCM-based tools, highway safety manual (HSM)-based tools as well as microscopic simulation (microsimulation) tools. Chapter 3 focuses on needed traffic simulation guidance not covered or has limited coverage in the Handbook and provided information that can be used as a basis for new sections in the manual including:

Chapter 4 presents an evaluation of traffic analysis platforms that could potentially meet the Department needs. The task identified a set of capabilities and use these capabilities to compare the analysis tools. The comparison among the traffic analysis tools in this document utilized the official manuals, user guides, and other documents. The main utilized documents are the Synchro Studio 11 User Guide (Cubic ITS Inc., 2019), PTV Vissim 2021 User Manual (PTV AG, 2021), Vissim's RBC User Manual (PTV AG, 2020), Highway Capacity Software (HCS) Users Guide (McTrans, 2019), North Carolina Department of Transportation (NCDOT) guidelines for TransModeler (NCDOT, 2016), and TransModeler Program Help documents. Chapter 4 also presents an evaluation utilizing model runs to test the tool's consideration of selected features.

Chapter 5 reports on the results of Task 4 of the project, aiming to provide direction on the application of Multiresolution Modeling (MRM). This effort will build on recent national effort funded by the FHWA that provided a review of the state of practice, guidance, and case studies for the use of MRM (Hadi et al., 2022a, 2022b; Zhou et al., 2021). This chapter includes the followings:

- Recommend Guidance based on the recently completed FHWA project on MRM
- Develop methods for integrating crowdsourced data from a third-party data vendor in the process of estimating the origin-destination matrix estimation (ODME) process required for the MRM for the modeled scenario(s)
- Assess the use of crowdsourced data platform obtained from third-party vendors to estimate segment level daily and hourly volumes.

Chapter 6 identifies the needs of the FDOT in traffic simulation training. Training is needed to build a robust workforce within the FDOT and its public sector partners and consultant, which is needed to maintain and advance traffic analysis and simulation capabilities. Currently, there is a limited Department sponsored training for micro-simulation and multiresolution modeling training. Chapter 7 provides recommendations for an analysis, modeling, and simulation (AMS) project clearinghouse for archiving and maintaining data, performance measures, analysis files, and documents.

CHAPTER 2: IDENTIFICATION OF FDOT NEEDS AND APPLICATIONS

2.1 INTRODUCTION

This Chapter reports on the results of Task 1 of the project. This task involves conducting a web-based survey of modelers from around the State of Florida using an On-line Survey platform, in addition to on-line interviews with selected users. The goal was to identify how simulation modeling is applied and the needs of simulation modeling in Florida.

2.2 DETAILS OF THE SURVEY RESPONSES

About 61 responses were received to the survey questionnaire, providing important information to this study. This section provides the details of the responses to the survey questionnaire.

2.2.1 Participant Attributes

Table 2-1 shows the number of the respondents by agency type. 57% of the respondents were from public agencies and 39% were from private agencies with the remaining 3% not disclosing their affiliations. Figure 2-1 indicates that 56% of the respondents are experienced or power users of simulation and only 14% are relatively inexperienced or have no experience in simulation models. As shown in Table 2-2, the respondent's agencies perform 3,339 simulation projects per year. 53% of these models have 10 junctions or less and only 13% of the models simulate more than 30 junctions.

Table 2-1 Number of agencies by agency type

Type	Frequency	Percentage of Total
Total Responses	**61**	**100%**
FDOT	**23**	**38%**
Florida Turnpike	**5**	**8%**
Counties and Cities	**4**	**7%**
MPOs	**3**	**5%**
Consultants	**24**	**39%**
Did not disclose agency name/type	**2**	**3%**
Public Agency (FDOT, Turnpike, City, County & MPO)	**35**	**57%**
Private Agency (Consultants)	**24**	**39%**

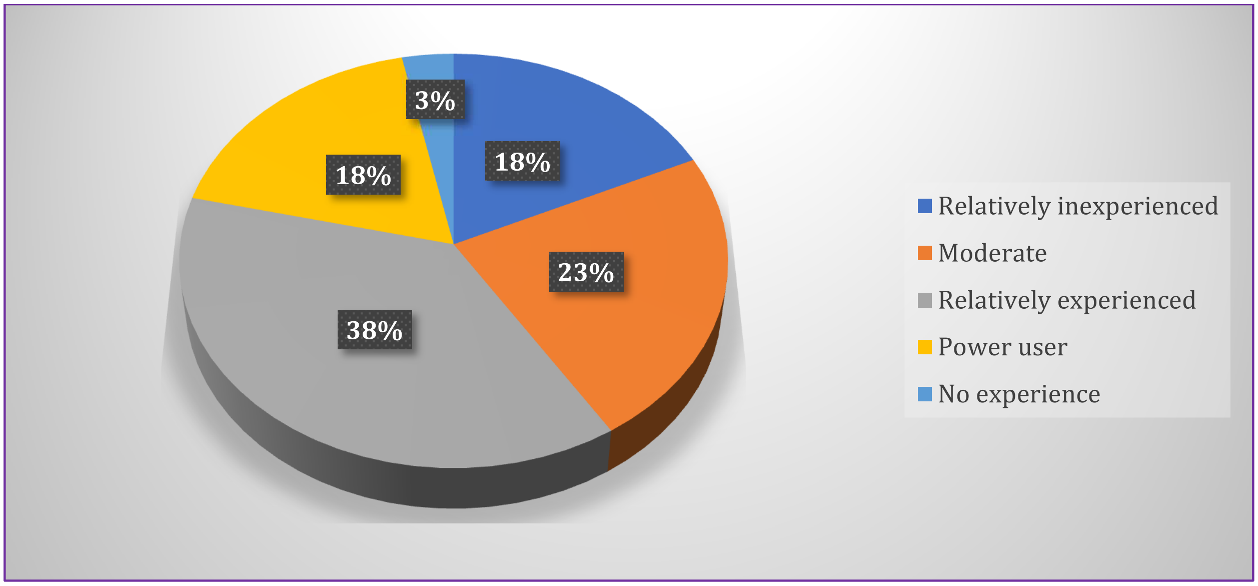


Figure 2-1 Simulation experience of the participants

Table 2-2 Number models per year categorized by the number of junctions

Options	No. of Responses	Percentage
Models with 1-10 junctions	1785	53%
Models with 10-30 junctions	1123	34%
Models with 30+ junctions	431	13%
Total	**3339**	**100%**

2.2.2 Analysis Types and Tools

This section discussed the types of analysis and the associated tools used by the agencies. Table 2-3 indicates that about 80% of the respondents utilize microscopic simulation models in their analysis and 88% utilize macroscopic models such highway capacity analysis and Synchro modeling. It is very interesting to note that 21 of the respondents (about 35%) said that they use mesoscopic simulation models and multiresolution modeling with 14 (about 24%) saying that they use dynamic traffic assignment (DTA). As discussed, next, most of these users use Cube Avenue. When asked about the utilized simulation tools, the highest percentage indicated using Vissim (81.4%), followed by SimTraffic (57.6%), and followed by CORSIM (39%). Nine (15.3%) and four (6.8%) of the respondents use TransModeler and Aimsun, respectively. 16 of the respondents (27.1%) use the mesoscopic simulation based DTA model Cube Avenue. Only one respondent utilizes DTALite, and two respondents use VISUM. This indicates that the main experience with Mesoscopic simulation in Florida is with Cube Avenue. Table 2-5 shows that the most used tool in conjunction with simulation is Microsoft Excel, although a small number of responses mentioned using other tools like R, Python, Microsoft Access, ELToD, ArcGIS, the Highway Capacity Software (HCS), and Synchro.

Table 2-3 Utilized analysis type

Types of Models	No. of Responses	Percentage
Macroscopic models (such as the tools that implement HCM facility procedures including FREEVAL, HCS, Synchro, etc.)	52	88.1
Mesoscopic models	21	35.6
Microscopic models	47	79.7
Dynamic traffic assignment	14	23.7
Multiresolution simulation modeling (Using levels in sequence Macro → Meso → Micro)	20	33.9
Hybrid simulation modeling (Using two various levels in the same run)	5	8.5

Table 2-4 Utilized simulation tools

Simulation Software	No. of Responses	Percentage
CORSIM	23	39.0
SimTraffic	34	57.6
VISSIM	48	81.4
TransModeler	9	15.3
AIMSUN	4	6.8
Dynameq	0	0.0
Cube Avenue	16	27.1
ELToD	2	3.4
SIDRA	1	1.7
Synchro	3	5.1
DTA Lite	1	1.7
SUMO	1	1.7
VISUM	2	3.4
FREVAL	1	1.7
S HCM	2	3.4
Voyager	1	1.7
INTEGRATION	1	1.7
TRANSYT 7F	1	1.7
Tru-Traffic	1	1.7

Table 2-5 Tools used in conjunction with simulation modeling

Additional Data management and Post-processing Tools	No. of Responses	Percent age
ABM	1	1.3%
Cube Voyager (CFRPM, etc.), TMCs, link counts (FDOT's FTI, SCTPO).	1	1.3%
Internal Tools	1	1.3%
Open-source software	1	1.3%
SAP Power-bi	1	1.3%
Seminole County Databases, FDOT model, Metroplan model, HCM	1	1.3%
SIDRA	1	1.3%
Turns, TRANSYT 7F	1	1.3%
ArcGIS, ArcMap	2	2.6%
ELToD	2	2.6%
Synchro	2	2.6%
Trafficware's ATMS.now and Traffop ATSPM	2	2.6%
HCS	3	3.9%
Microsoft Access	3	3.9%
Python	3	3.9%
R	3	3.9%
Microsoft Excel	11	14.3%
No	12	15.6%
N/A	26	33.8%

2.2.3 Guidance Utilization

This section discusses the responses to questions about the utilization of state and national guidance for various simulation project tasks. When asked if there is a process or processes by which the agency decides on the use of simulation modeling versus other analysis procedures, 57% (24 responses out of 42) indicate that they do not use any guidance for deciding on the use simulation versus other analysis methods. This response was consistent between public and private agencies. Rather, they use other methods as listed in Table 2-6 including deciding based on project's scope, needs, complexity, and level of analysis; consultant recommendation; availability of budget; acceptability to the agency; and the level of congestion. The remaining respondents (22 overall) specified using the following guidance from the highest use to the lowest use to decide on using simulation: FDOT Traffic Analysis Handbook (13 responses), other FDOT related guidance (4 responses), FHWA documents (3 responses), and FDOT Project Traffic Forecasting Handbook (2 responses.)

Table 2-6 Bases for the decision to using simulation

Decision Making Guidance	No. of Responses	Percentage with Yes
Project's scope, needs, complexity and level of analysis	13	31%
FDOT Traffic Analysis Handbook	7	17%
Interchange Handbook & related guidance	4	10%
Consultant driven	3	7%
budget of the project	3	7%
Project Traffic Forecasting Handbook	2	5%
Agreed Methodology and acceptability to reviewing agencies	2	5%
Software tool based on project type	2	5%
FHWA Documents and supported software	1	2%
FHWA Volume II	1	2%
FHWA Volume III	1	2%
Saturation Condition	1	2%
HCM Guidance	1	2%
PD & E studies, evaluation of alternatives	1	2%

Only *36 (61%)* of the respondents said that they use formal guidelines or manuals for the calibration and validation of the models. When asked to specify the names of the utilized guidelines or manuals, 15 of the respondents said that they use the FDOT Traffic Analysis Handbook, as shown in Table 2-7. This handbook is the most used document for the calibration and validation followed by the FHWA Traffic Analysis Toolbox followed by the FDOT Traffic Forecasting Handbook. Overall, it seems that the percentage of the respondents using any guidance for model calibration and validation is not as high as expected. Table 2-8 indicates that the highest use of the guidance is for model development, calibration, and validation. Other reported uses are the selection of measures of effectiveness (MOEs), selection of appropriate tool, quality control of model input, and assisting in reviewing simulation models and alternative analysis.

Table 2-7 Guidance used in simulation calibration and validation

Options	No. of Responses	Percentage
AASHTO Standard	1	2%
FDOT Intersection Handbook	1	2%
FDOT Q/LOS Handbook	2	4%
FDOT Traffic Analysis Handbook	15	28%
FDOT Traffic Forecasting Handbook	5	9%
FHWA Traffic Analysis Toolbox	6	11%
FHWA Traffic Analysis Toolbox Volume III	3	6%
FHWA Traffic Analysis Toolbox Volume IV	1	2%
FHWA Traffic Analysis Toolbox Volume V	1	2%
FHWA Traffic Analysis Toolbox Volume VI	1	2%
FSUTMS Model Calibration & Validation Standards	2	4%
HCM	1	2%
Internal guidelines	1	2%
Maryland DOT SHA VISSIM modeling guidance	1	2%
NCHRP 255 & 765 methodology	2	4%
North Florida TPO Technical Reports, FDOT	1	2%
ODOT VISSIM Protocol	1	2%
Simulation Software Manual	3	6%
Turnpike company set guidelines	1	2%
VDOT VISSIM User Guide	1	2%
VISSIM guidelines	1	2%
Wisconsin DOT Calibration-Validation Protocol	1	2%
WSDOT VISSIM Protocol	1	2%
Total	**53**	**100%**

Table 2-8 Guidance use in simulation tasks

Application of Simulation Guidelines	No. of Responses	Percentage
Model development, calibration, and validation	10	37%
Selection of MOEs	2	7%
Selection of appropriate tool	2	7%
Coordination with guidelines	2	7%
Quality control of model input	1	4%
Follow central office or agency protocol	2	7%
TAZ, Lane, Intersection, and Facility Standards	1	4%
Update, modify or develop forecast approaches	2	7%
Follow detailed procedures or methodologies	5	19%
Total	**27**	**100%**

When asked about the experience and deficiencies in the guidance, the following was provided:

- The scope of the guideline is limited (2 respondents)
- Need more focus on data given that there is not enough calibration data (2 respondents)
- Some of the documents are inconsistent (2 respondents)
- Lack of specific examples to model certain unique situations
- Very little focus on public transit, pedestrian, bicycle, and other modes of travel
- Need to provide more detailed guide by the modeled alternative type
- Additional guidance needed on mesoscopic modeling (2 respondents)
- Good to have an update of the guidance and put it online

As shown in Figure 2-2, when asked if there is a need for Florida general simulation guidance or tool-specific guidance, 66% said there is a need for both, 25% said that there is a need for general simulation guidance, and 9% said that there is need for just tool specific guidance.

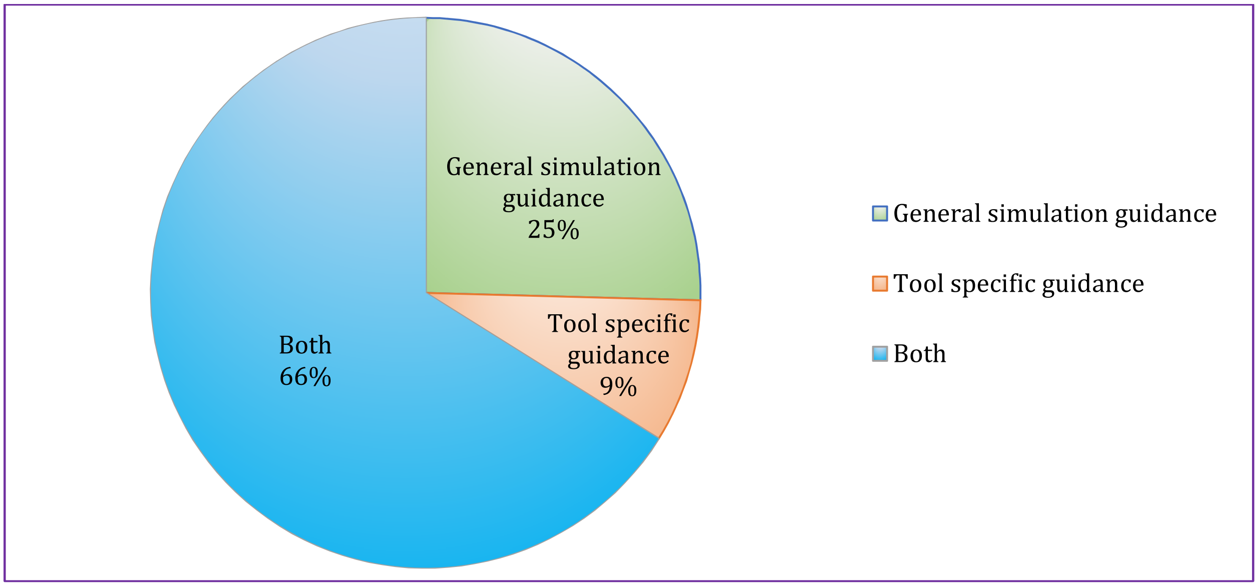


Figure 2-2 Participants opinion about the type of simulation guidelines required in Florida

2.2.4 Model Development and Calibration

Table 2-9 shows the type of data used in the development and calibration of simulation models. 91.5% of the survey respondents said that they use volume count studies and 81.4% said that they use field observations. With regard to travel time measurements, 60% use travel time studies, 60% use automated travel time data collection such as from Bluetooth readers, and 61% use travel time data from third party vendors. About 44% of the respondents said that they use counts from ITS detectors and 39% said that they collect heavy vehicle information. It is interesting to see that about 47% of the respondents use O-D data from third party vendors and about the same percentage use O-D data from demands models. 39% of the respondents use ODME procedures. Four users said that they use individual vehicle trajectory data, but it is not clear how do they use this data.

Table 2-9 Type of data used in model calibration and validation

Options	No. of Responses	percentage
Turning movement and automatic tube counts	54	91.5
Travel time test car studies	34	57.6
Observations of queues or speeds	48	81.4
Counts from ITS detectors	26	44.1
Heavy vehicle composition by class	23	39.0
Travel time data from Bluetooth/Wi-Fi readers	34	57.6
Travel time data based on third-party vendor data (e.g., HERE, INRIX, NRDPMS)	36	61.0
O-D data based on third party vendors	27	45.8
O-D data obtained from demand models	28	47.5
O-D data from demand models and refined using OD matrix estimation (ODME)	23	39.0
Trajectory vehicle data that track vehicles at a fraction of second intervals.	4	6.8
Streetlight	1	1.7
ABM	1	1.7
RITIS	1	1.7
O-D data collected by FDOT	1	1.7

Some of the comments on the utilized data type are listed below:

- Arterial third-party data is inaccurate and FDOT detection data is limited. Taking large data sets, removing noise, and consolidating to use cases for scenario generation needs more guidance.
- User needs to be careful with data from third party vendors as data may average across all lanes, does not have small enough segments in areas with closely spaced interchanges, and outliers may be removed by filtering.
- Data availability is limited.
- Consistency is an issue.
- Raw O-D data is hard to get.
- Data sharing can be important.
- Heavy vehicle data may be available from American Trucking Associations (ATA).
- Some users that in the past used actual travel time data collected in the field but recently are using third party data.

When asked to comment on the issues and needs in the calibration of the simulation models, the followings were mentioned.

- There should be flexibility to decide on the calibration method on a case by case, without mandating a procedure.

- Guidance documents from other states such as Oregon were utilized for VISSIM calibration.
- There is a need for transparency and documentation by the modelers of the calibration process, so the reviewer can follow along with the analyst's assumptions and methods. The reviewer does not necessarily know how to run the model but must review models built and run by others (consultants) and need to be able to check the work and have confidence the assumptions, inputs, and results or outputs are valid.
- There are a need calibration targets that have a range.
- There is a lack of guidance and training for junior engineers.
- Need better data to calibrate
    - There is a need for more frequent data and situational-based data for special events simulation (multiscenario simulation)
    - There is a need for consistency in data cleaning methodologies when data is purchased.
    - There is need for more discussion of usable data and what constitutes useable data by type.
    - General calibration data for major Florida highways could be categorized by regions and centralized to ensure consistency.
    - FDOT is in a leadership position because of their willingness to invest in data, i.e., multiple days of counts, etc. There is far too much reliance on existing count data for model calibration (as well as traffic forecasting) which leads to numerous issues down the road related to questionable count data. Fundamentally, simulation model cannot be fully calibrated if the analyst is using an ad-hoc collection of counts obtained over a 1-to 3-year time period. How do we know if the model is really calibrated if you are using travel time data from Nov 20 and count data from Aug 18?
    - There is a need for a lot of data: reliable travel time / travel speed data, field observations to identify turning speeds / ramp speeds, queuing behavior, etc. Calibration of multi-hour models can take a lot of time.
    - Better O-D data patterns is always a desire.
    - Expansion of count data locations with more data points throughout the year instead of three-day counts which sometimes prove to be not useable for annual forecast analysis. More Time of day counts at strategically selected locations would help.
- When attempting to achieve accuracy criteria, results can be inconsistent when using multiple variables.
- Avoiding over calibration is important. Most guidance is based on doing more.
- A lot of people only see a need to calibrate to volumes, but that is not enough. At a minimum, travel time should be calibrated. The cost difference between a good model and a great model is in the amount and types of data collection.
- A step-by-step guide for calibration would be helpful, in order to determine which field-measured metrics should be used under which circumstances. Detail on when to supplement system-wide calibration (e.g., travel time through a corridor) with local calibration (e.g., queues for specific turn lanes) would also be helpful.
- Guidelines on acceptable ranges for various Driving Behaviors parameters would be helpful.

- Demand forecasting model is often too general for small area modeling and does not take into account local area trips well. The specifications of TAZ's often lead to misleading results. These models can overestimate or underestimate the demands significantly.
- Too many users only use the defaults resulting in invalid results.

Table 2-10 shows the performance measures reported by the respondents as currently used or needed based on the output of simulation models. Queue length, travel time, and level of service are the most widely used measures. Interestingly, reliability is ranked fourth after these measures as a needed measure (45.8% of the respondents) followed by the number of stops. Also, interesting is that about 19 respondents reported the need to report emission and safety surrogate measures.

Table 2-10 Performance measures currently used or needed based on the output of simulation models

Performance Measures	No. of Responses	Percentage
Queue data	51	86.4
Travel time measurements/ Delays	56	94.9
Number of stops	22	37.3
Reliability	27	45.8
Emission	11	18.6
Safety surrogate measures	11	18.6
Level of service	47	79.7
speed, travel time	4	6.8
Travel Patterns	2	3.4
Unmet Demand and Exit Volume*	1	1.7
throughput, volume*	1	1.7
Latent demand, served demand	1	1.7
density for weaving	1	1.7
Lane changing pattern	1	1.7
Delay of Pedestrian, Bike, transit	1	1.7

2.2.5 Agency Processes and Resources

When asked whether the simulation models are being generated in-house or consultants, Figure 2-3 shows that 35% of the public sector respondents reported that both the development and review are done in-house, 41% reported development by consultants but the review in house, and 24% reported that both the development and review are by consultants. Figure 2-4 indicates that 64% and 88% of the public and private sector respondents, respectively, said that they have sufficient staff to develop and review the model. However, as indicated in the interview results section presented later in this document, the public sector responses to the survey questions in Figure 2-3 and Figure 2-4 overestimate the public agency capabilities and contribution to model generation. This is possibly because the public sector respondents include their in-house consultants when reporting on the public agency model generation and capabilities.

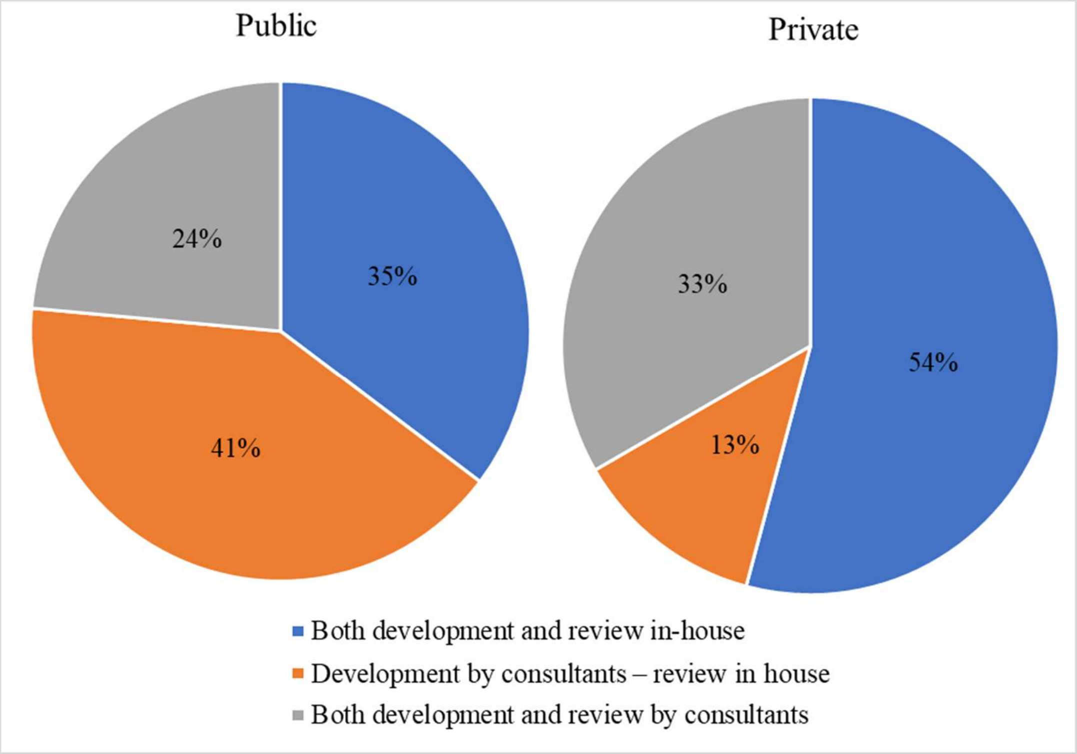


Figure 2-3 How simulation models are generated

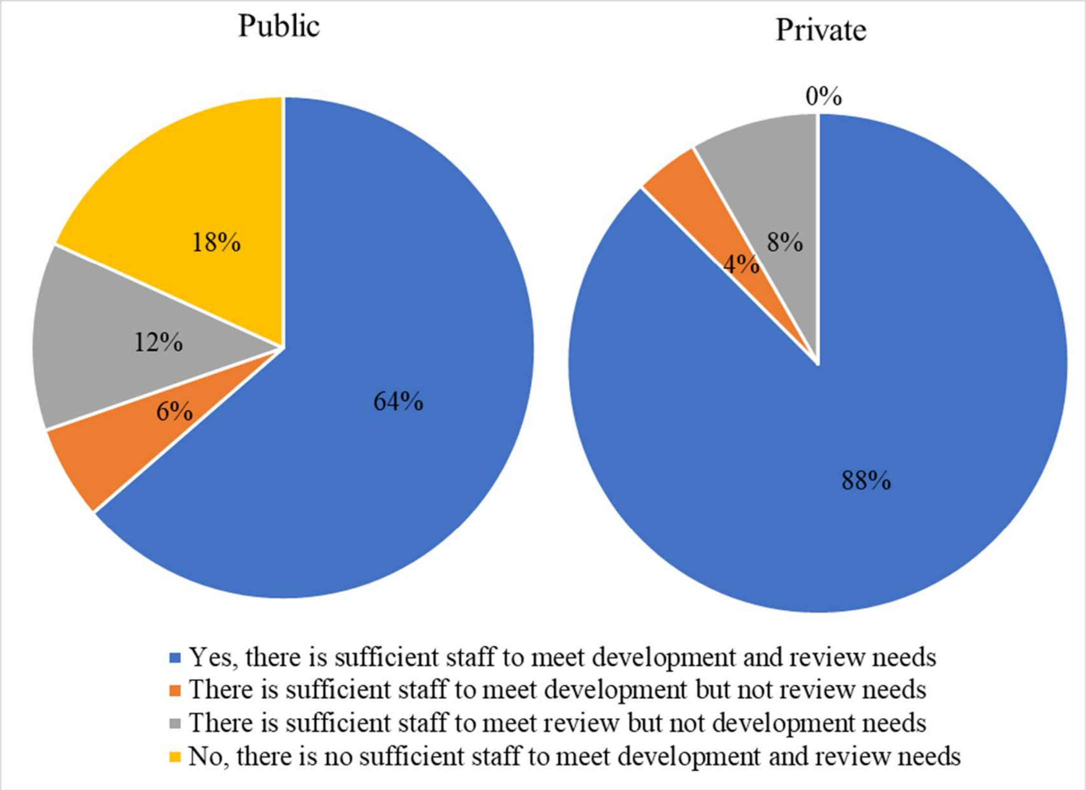


Figure 2-4 Distribution of availability of sufficient skilled stuff for modeling

The following comments were given regarding whether the agency and consultant have sufficient technical staff to develop and review models to meet simulation needs.

- There are only a handful of consultants that are trusted and can present the results in an easy-to-understand format.
- Interchange projects are commonly reviewed by consultants and not FDOT staff, which might be due to lack of staff to review all models. FDOT staff may lack the appropriate training and experience to review or develop models.
- In some cases, the public agency has staff to review but not enough experience to develop the models.
- The Turnpike has multiple consultant groups for model development and review. They are employed based on the project.
- The public agency may have staff with microsimulation experience but due the nature of complex models and time to perform other functions most of the time the review is assigned to a consultant.
- The department's move to having consultants develop models to give to project consultant teams is eroding the ability to develop consultant technical knowledge outside of those working on model development.
- Staff involved with traffic operations have varying levels of expertise to develop and/or review traffic demand and/or simulation models.

When asked if the agency have an adequate budget to meet simulation needs, 71% of the respondents said yes, they have sufficient budget but not in all scenarios. The following comments were given in this regard.

- Sometimes the budget is sufficient but not always. Ultimately, we do the best we can with the budget we have.
- Money is never the problem. The issue is expertise, allowable time, and lack of objective
- Budget adequacy varies by project. We only use simulation if there is sufficient budget, if not another platform is used.
- At the current levels, there is enough budget but with the move to more multiresolution modeling the budgets may not be adequate for that type of modeling.
- It is expensive to do micro-simulate and because of that the model is built for a one-time project like a PD&E and only run for the No build alternative and one Build alternative instead of being used to run different variations of the Build or interim phasing of the Build alternative.
- There is always a desire to have a larger budget to obtain more and better data to support the model development and application. We would always desire to have more budget to put towards additional features, calibration, or validation work on every model for every project. We make the budget available work but probably most of us answering these questions are not directly involved with the budget.
- Budget is not available to send staff to train on the models.
- We appreciate the Central Office funded initiatives to train staff who face an increased need to primarily review models developed by consultants and in some instances have the autonomy to prepare such models themselves as needed.

- Our organization typically has enough funding for 2-3 licenses for a single platform. Version upgrades are typically funded for every 2 to 3 years.

When asked about how to estimate the number of hours required in the analysis, the following was reported.

- The estimates are based on experience from previous studies and the magnitude of the area and number of alternatives tested.
- Agency estimates should only be developed by users with significant experience in multiple simulation models. Otherwise, there is usually not enough budget allocated to properly calibrate and validate the models.
- The consultants provide an estimate of what they think the number of hours to run the simulation will be. There is some guidance in the Traffic Analysis Handbook.
- For microsimulation it is a combination of number of intersections, weave sections, access/egress points and overall size of the network.
- The estimates depend on the tool, the level of detail required in the analysis, number of times it will need to be run, number of phases, number of analysis years, number of alternatives, output, etc.
- The required effort is based on the desired product(s) to be delivered for each project and level of the deliverable (e.g., a feasibility study would require less hours than an investment grade study).
- A number of work hours is determined for each junction based on previous project budgets and multiplied by the number of scenarios to be analyzed. The number of hours for existing is typically higher for existing conditions due to calibration efforts and depends on the number of metrics used to calibrate and validate.
- Estimates are included in the Traffic Impact Study.
- Estimates are highly dependent on the network size, quality of input data, and calibration thresholds.

As shown in Table 2-11, when asked about the training needs, about 44% of the responses said that there is a need for a general simulation modeling training. About 10% specified training on specific advanced topics like dynamic traffic assignment, automated output processing, application program interface, and modeling complex intersection and interchange designs. About 20% specified tool specific training.

Table 2-11 Training needs

Full Response	Response	Percentage
Activity Based Travel Demand Modeling	2	3.3%
Alternative/complex intersection and interchange designs	1	1.6%
Application Program Interfacing training	1	1.6%
Automated output processing	1	1.6%
Basic and advance training	3	4.9%
Dynamic Traffic Assignment	1	1.6%
FDOT sponsored training	1	1.6%
General micro simulation training/principles.	8	13.1%
General Modeling trainings	5	8.2%
Have not done any modelling or simulation.	1	1.6%
macro and mesoscopic modeling	2	3.3%
Model Calibration	3	4.9%
SIDRA and HCS	1	1.6%
SimTraffic and Synchro	2	3.3%
Statewide training	1	1.6%
Traffic forecasting, analysis,	1	1.6%
TransModeler	1	1.6%
VISSIM and Other PTV Products	9	14.8%
No Need/ N.A.	17	27.9%
Total	**61**	**100%**

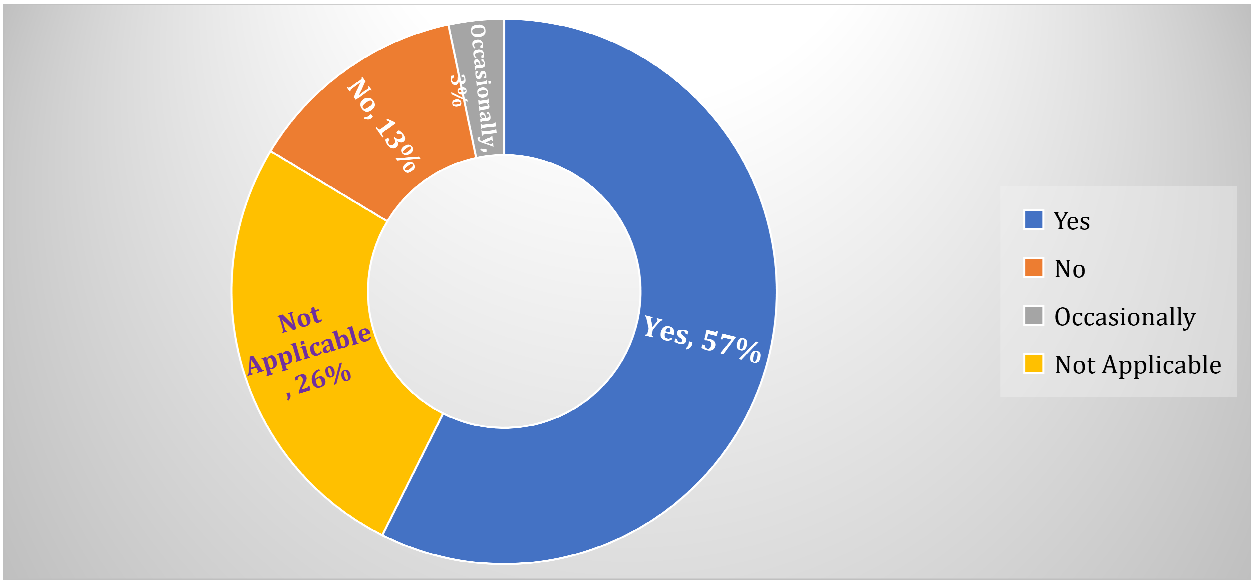


Figure 2-5 Agencies' responses about archiving models after completing a project

2.2.6 Future Year Demand Forecasting

Future demand forecasting can be a critical component of a simulation project. When asked about the utilization of demand forecasting model outputs as inputs to simulation modeling, the following was reported.

- The demand forecasting models are not accurate enough to produce design traffic for modeling.
- The demand forecasting model output needs post processing to be an input into the microsimulation.
- Our district currently utilizes daily travel demand models so there is significant post processing to obtain the hourly volumes for input into microsimulation models. There is no use of meso models currently in the district.
- Being able to utilize the output for input to another model sometimes is not compatible and must be transformed. This can be difficult and time consuming. Sometimes the time periods do not match, or the breakup of trips is different for model input requirements and must be processed to meet the input requirements (trip types, modes, etc.).
- Regional models are unconstrained - model output volumes are higher than capacities and the unmet demand cannot be correctly represented and simulated.
- The regional models are not validated to intersection level for peak hour.
- In Traffic Impact Analysis, demand forecast modelling is often overridden to conform to engineers' judgement and experience. This is justifiable as travel-demand models themselves require calibration. It is always best to utilize trends and data collected in the field but using demand forecasting models can be justifiable for time saving as long as the methodology is reasonable.
- Most project delays result from the quality of demand model results.
- Generally, not detailed enough. Need 15-minute intervals for volume.
- You need an experienced forecaster involved in the effort otherwise you will have Traffic Engineers and analysts taking trip table output directly from regional travel demand models and trying to apply it to detailed corridor simulation models which never works out well. You have to have someone involved who understand travel demand and simulation models to bridge this gap.
- In the past the difficulties have been the ability to easily utilize demand output as input files. There have been compatibility issues.
- Demand forecasting has historically generated daily volumes, so converting these to peak hour volumes, and especially peak hour turning movement volumes, has been somewhat of a challenge. More travel demand models are starting to have peak hour outputs now.
- I would almost never use travel demand forecast as input for simulation output. One is too general for the other.
- Demand forecasting models are often too general for our small city and does not consider local area trips well. TAZ's often lead to misleading results.
- Identifying the demand for shoulder hours for future years is challenging
- The failure to adopt NCHRP 765 across the state leads to odd results for model forecasting, especially when 2010 base year is used in 2019/2020.
- The models overestimate/underestimate traffic demands.

Related to the above questions, the users were asked about the procedure used and experience in modeling future year networks and demand inputs to the simulation model. The followings are responses to the question.

- Develop design traffic considering model data, development data, and historical trend lines.
- Develop traffic utilizing the locally adopted model or either growth rates for future year analysis or using that into the existing calibrated model while documenting any changes to any calibration factors.
- Use the guidance in Traffic Analysis Handbook.
- Obtain the future year demand traffic data from the traffic forecast memo prepared by the consultant who collected the data.
- Use growth rates applied to most recent valid count data as inputs to simulation model
- Convert the output AADT from the model into DDHVs using FDOT approved methodology
- Review the model input data, compare with future regional plans, and update the data as needed to best represent the future planned transportation environment
- Use self-developed Excel spreadsheet work together with ODME process
- Use Florida Project Forecasting Handbook
- Use demand forecasting model outputs and normalize using the targets from counts or the design hour traffic.
- Verify future peaking characteristics against existing ones to ensure properly applied
- Coordinate with our travel demand forecasting group
- Evaluate model growth rates and compare to historical growth based on counts. Then make a determination of whether to forecast the design year via the model or apply growth rates to existing counts. Most forecasts use the model with post processing adjustments. This is followed by the process of developing the design hour directional volumes - DDHV's. For a simulation model 3+ hours are generally needed, and this requires a peak period forecast including the "shoulders" of the peak hour.
- Typically, use tools like trends analysis or TURNS to develop future year AADT and TMCs.
- This varies by project and the demand to capacity ratio for the corridor. This can include using Matrix Variator for spreading the peak, a DTA, manufactured factors based on samples in more congested areas in the same corridor. Lower the K factor based on data for the corridor and other steps.
- This requires Guidance
- We save the existing calibrated models and update the volumes based on future year forecasts. We use NCHRP 765 or FDOT procedures to post process travel demand model output and developing intersection forecasts.
- Use historical data to project growth trends to determine demand inputs. Network modifications are made based on known development projects and LRTP.
- Apply K and D factors to model AADT at intersections, use existing turning movement count percentages to assign approach volumes into turning movement volumes... use

weighted approach volumes as supplemental consideration, trying to balance in/out volumes for total intersection.

- Volumes are post-processed in Excel, then applied to the VISSIM model.
- Draw %growth from a travel demand model and estimate the future input data.
- Design traffic determination. But often time microsimulation model simple can't handle that many volumes, so we would slow load the network with volumes and gradually increase volumes. The main goal is not about understand the exact operation but more comparison of alternatives,
- No formal procedure - relies upon consultant's expertise. Limited experience in modeling for future years.
- sometimes trial and error to see what makes sense
- Use NCHRP 765 + Turns 5 + in house spreadsheets for balancing

2.2.7 Additional Needs and Issues

This section discusses some of the additional needs and issues related to simulation models. Table 2-12 and Table 2-6 show that about half of the respondents are interested in emerging technologies such as connected. Automated, and electric vehicles. 26% are highly to extremely interest. More than half of the respondents are not interested in modeling emerging technologies, at least at the present time.

Table 2-12 Participants interest towards emerging technologies

Level of Interest	Response	Percentage
Extremely Interested	3	5%
Highly Interested	13	21%
Interested	5	8%
Moderately Interested	4	7%
Likely Interested	5	8%
Not now, may be in future	3	5%
Not Interested at all	28	46%
Total	**61**	**100%**

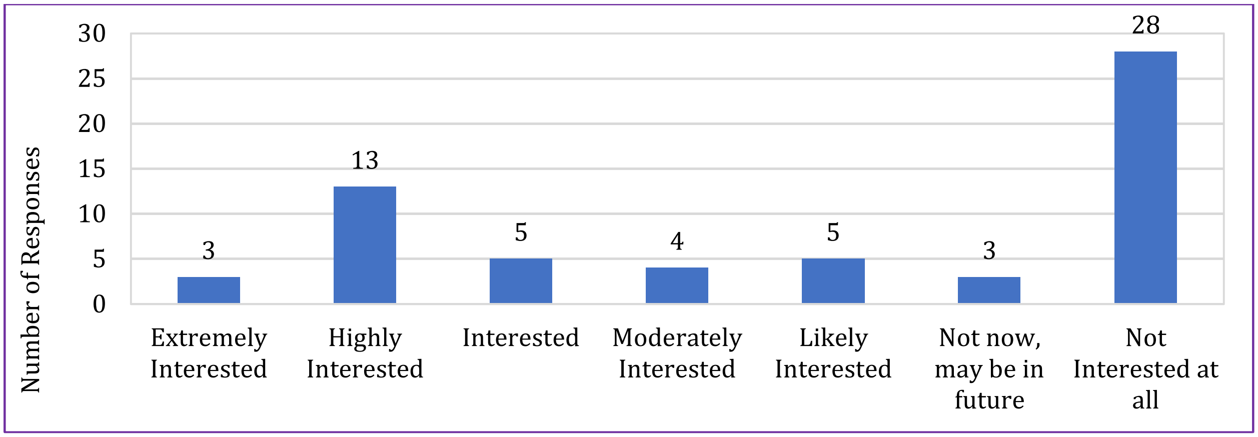


Figure 2-6 Participants interest towards emerging technologies

When asked about additional issues, barriers, needs, and concerns facing the agencies in using simulation, the followings were reported.

- Moving to VISUM should definitely help since we rely heavily on VISSIM to complete analysis.
- Not enough internal expertise for coding, running, and interpreting the results of the simulation model.
- Training and lack of experience. Most of the time FDOT staff are told to use consultants to develop and review the models instead of giving them the appropriate training.
- Cost for any increase in use will be an issue with our budgets.
- Changing data requirements and availability of input data.
- Needs for recommendations of DTA software platform
- The impact of shorter project schedules. Simulation models are time consuming.
- Reliability and scenario-based analysis is coming.
- There is so much of data and most of it is thrown away due to lack of experience manipulating it.
- The world is creating more specialists while the agency staffing is getting smaller.
- Constant challenges with maintaining software and licenses, etc.
- Getting staff trained and really understanding what the models are saying. There is too much reliance on models now and not enough on engineering judgement in the planning process.
- Cost barrier to expanding access to all employees. We are limited by the number of licenses/computers with simulation software.
- The amount data required for a good model, the time it takes to calibrate a model, professionally trained modelers, and series of reviews to ensure that the models are built correctly before the calibration effort begins.
- More training is needed for agencies. Many agencies fail to see how useful microsimulation can be but can also fail to see when it is not needed.
- Budget issue.
- Simulation is a mere visualization of space in time in a network. It is one of many factors that goes into planning and engineering. However, not the end all decision making. Transportation systems are very complex and using a tool that pretty much only looks at cars is a dying exercise. LOS should not be the only MOE. Other factors beyond modeling that affect safety (vision zero), walkability, livability, environmental sustainability, and quality of life factors are much more important.
- Funding is a major constraint.
- Need to explain to clients the relative results. (e. g. 2 secs may be the difference between LOS D and E, but it is not the end of the world)
- Training and technical staff
- Limited software, limited training

2.3 STAKEHOLDER INTERVIEWS

Following the survey discussed in the previous sections, this research conducted interviews with major stakeholders of the potential enhancements to the simulation processes in Florida. The stakeholders cover the FDOT planning, design, management, and operations departments, as well as two metropolitan planning organizations and two consultants. The interviews were one hour to one hour and half in length. The following is a list of the stakeholder agencies.

- Bowman, Jenna, FDOT System Implementation Office
- Ponnaluri, Raj, FDOT TSM&O and CAV programs
- El-Urfali, Alan FDOT Traffic Engineering Studies
- Knight, James, FDOT District 2 Planning, Design, and Engineering (PD&E)
- Bikram Wadhawan, Hanson Inc.
- Velasquez, Andrew, Segovia, Cesar, Mulandi, Jimmy, Segovia, Cesar, and Emam, Emam B., the Florida Turnpike Enterprise modeling consultant team.
- Fernandez, Wilson A. Miami-Dade County Transportation Planning Organization (TPO)
- Nick Lepp, Orlando Metro planning Organization (MetroPlan)

2.3.1 Agency Processes and Resources

The interviews revealed that simulation analysis is used by the various offices of the FDOT interviewed, which includes the system planning office, PD&E, TSM&O and CAV, and traffic engineering studies offices. Traditionally, the MPOs have utilized demand forecasting models. Some metropolitan planning organization (MPOs) have a focus on major transit improvement including light rails and Bus Rapid Transit (BRT) with bus lanes. There is also an interest in using simulation by MPOs, although the extent of this use has been limited. Others are very interested in evaluating TSM&O and CAV impacts. Simulation can play an important role in these evaluations. Some cities are interested in using simulation for evaluating alternatives including TSMO alternatives, however they sometimes do not have the needed funding for this and the MPOs may work with them on this.

The simulation models in Florida are mainly developed by consultants. Not all consultants have the capability to develop simulation models, particularly for large works. The review process is sometime done by a third party (another consultant) and sometimes by the public agency. In general, experience with reviewing and running the model in the public agency is limited and the review sometimes is limited to checking the consistency and how logical are the model results as reported. The manager looks at overall analysis results without going to the model itself. With regard to the use of a third party for review, although it has been used, it adds a significant cost to already modeling efforts. On the other hand, maintaining experts in the simulation in the public agencies can also be very expensive and difficult, particularly with the competition with the private sector on talents in this area.

Some agencies have adopted detailed processes for the review. For example, the System Implementation Office at the central office assigned a consultant to review the models required to produce the Interchange Modification Report. The consultant does a reasonableness check to confirm nothing out of the ordinary and check the inputs, traffic building in the peak hour, and dissipation of traffic before the end of simulation. In this process, the developers of the models are required to generate visualization of such as heat maps, lane schematic, etc., to be checked in the review. An important consideration is the reporting of the latent demand. If this is not reported and considered, the improvement alternative may look worse than the No-Build alternative because a large proportion of traffic may not be able to enter the network in the No-Build alternative. It was reported that 5% to 10% of the project budget should be assigned for the review. The Florida Turnpike Enterprise (FTE) has also established a documented quality check process.

There is a need for good coordination between planning and operation offices. Good simulation practices can better connect different FDOT departments and partner agencies can connect planning and operations.

Simulation can also be used to produce information to support the development of guidance, criteria, and warrants. Examples are to develop criteria for right-turn-on-red, pedestrian timing configuration, signal priority, etc. considering both mobility and safety. Simulation can also be used to identify performance modification factors for use in sketch planning tools. Such factors can support the assessment of the return-on-investment. It was also stated that mainstreaming of TSM&O has been successful and can be used as an example for having effective simulation practices incorporated in various guidance, manuals, and processes. An excellent example is incorporating TSM&O in the PD&E manual.

There is a need to make the business case for using simulation in processes that are currently do not use simulation when it is needed. Proven cost effectiveness of the model level and tool utilization is critical.

An important aspect is the use of simulation to support the assessment of the impact and to support the deployment of new technology on mobility and safety. This was discussed by the FDOT traffic engineering and TSM&O managers for design and operation level of assessment of the deployments, as well as by the MPOs for planning level assessment. Examples of advanced technology and strategy applications that can benefit from simulation include dynamic shoulder use, express and reversible lanes, CAV impacts, automated traffic signal performance measures (ATSPMs) for arterial corridors, integrated corridor management, wrong way driving. Incident management, and ramp metering.

Some agencies reported that in a few cases, they used the same model in more than one project. This helped in the work and saved budget. However, it was mentioned that archiving the models has problems in that in some cases, old models may not be compatible with the new version of the software.

2.3.2 Guidance Utilization

There was a general agreement that the calibration criteria in the FDOT calibration guidance are good but sometimes discussions are needed to provide justifications if the criteria are not met. One opinion is that the model development and calibration do not have to be rigid. The calibration criteria should be flexible and should not be complex and hard to meet.

Since 2005, the FTE has developed and maintained a detailed internal simulation guidance as a living document. The guidelines are based on current practices and the guidelines of Florida and other states (e.g., Oregon), FHWA volume 3 (2003 version). The guidance is both general and software (Vissim) specific. It adds much more detailed step by step guidance to the 2014 FDOT Traffic Analysis Handbook

A new version of the FDOT Traffic Analysis Handbook has been updated and there is a draft version of the handbook under review by FDOT. This update is expected to be released around May 2021. The updated handbook will include new policies and chapters for modeling of managed lanes, performance measures other than quality of service for alternative comparison. Other sections of the manual were updated to reflect current information, but some sections/chapters have no major changes. CAV and multiresolution modeling will not be addressed in this version.

2.3.3 Analysis Types and Tools

Microscopic simulation has been used to support the evaluation of various design alternatives. In general, the selection of the tool type and tool is based on the judgment of the public agency and their consultant. Conditions that usually triggers the use of simulation may include closely spaced intersection, high demand to capacity ratios in urban areas, backups between intersections and/or interchanges complex system configuration, express lane use, etc. All of these factors are looked at in combinations.

In some cases, when using simulation, HCM analyses is performed for initial screening of the alternatives and simulation is used later for more detailed analysis. Simulation using SimTraffic is used in many cases for small projects where such use is adequate in lieu of the using more detailed analysis using software like Vissim or TransModeler analysis. For undersaturated conditions, HCM type of analysis can be adequate. The use of SimTraffic satisfies the Intersection Control Evaluation (*ICE*) requirements. SimTraffic is easier to use and allow the modeling of multiple intersections according to ICE requirements. However, SimTraffic cannot model the impacts of detailed operational features that may be important for the modeled scenario such as lane change distance, pedestrian, lane utilization, and pedestrian and multi-modal modeling. It appears that the degree to which more detailed microscopic simulation models vary by FDOT district. The specific type of modeling is usually agreed on for a project and the agreement is documented in a project memorandum of understanding (MOU). It was stated that it is useful to examine how the decision on using simulation is addressed in the Traffic Analysis Handbook (or other documents like the FDOT Planning, Design, and Engineering (PD&E) manual.

The use of multiresolution modeling with DTA and/or mesoscopic by the interviewed agencies seem to be limited. The exception is the FTE modeling group that successfully uses ELTOD, which is currently a macroscopic traffic model DTA tool. At least one of the other interviewed agencies reported that using ELTOD and DTA in one of their projects increased the budget significantly without adding significant benefits. The MPOs are also interested in mesoscopic simulation based DTA and look for additional information and guidance. For example, in preparation for this, Miami-Dade County TPO is collecting information at the intersection level (signal timing) in a new database. Such data and models can be used for both planning and traffic operations modeling.

ELTOD is now a network model and may be updated to use a mesoscopic model instead of a macroscopic model in the near future. ELTOD allows the consideration of time variant demands and better consider as performance and the associated values of time. In a multiresolution modeling, ELTOD can be used first for route assignment, then Vissim can be used for lane assignment and detailed microscopic simulation. The FTE team incorporated trip time in addition to toll utilities in the choice model. The team is also interested in looking at VISUM as part of the multiresolution modeling, as the regional models in Florida are converted to using this tool ELTOD has been used by few other districts and consultants like D1 and D7, according to the FTE team.

One of the areas of interest is to use DTA to determine the impact of lane elimination on demand shifts. However, this can be also done using machine learning, with the FDOT starting collecting and arching data for the before and after conditions.

When selecting the tool and analysis type; the ease of use, available expertise, and comfort level with the tool is important. Some tools require a lot of effort but provide limited additional benefits. The analysis may need three levels of tools with different levels of accuracy for different levels of the decision making. There is a need to justify the extra time and expense required for simulation from a return-on-investment point of view. This should be accompanied by a marketing campaign to communicate the benefits.

2.3.4 Data Needs

It appears that modelers increasingly using travel time data and partial O-D trip data from third party vendors. Data also start or will start to be available from other emerging sources such as automated turning counts, high-resolution controller data, connected vehicles, drones, high resolution sensors, work zone eye tracking etc. However, traditional methods of collecting travel time are still widely used. For example, travel time measurements using test cars is used with a minimum specified or calculated number of runs. It was reported that in some cases, data from third party vendors like HERE and INRIX are too aggregate in space since the measurement segments have fixed lengths that can be sometime too long.

The quality of the collected data from automated sources is questionable. In some cases, the data from third party vendors show that uncongested locations having congestion and vice versa. Data should be examined by an analyst that is familiar with the area. SunGuide detector volume counts also need examination, particularly with regard to volume counts. It was mentioned that the devices need frequent calibration (e.g., every three months). The data quality is different for different regions.

The O-D demands from third party vendors is also useful to adjust the demand matrix from the regional model, to be used as a seed matrix in the ODME, for selected link analysis, and to determine the temporal variations, possibly at the intersection level. However, this type of data also should be also examined for accuracy.

Although freeway mainline links have sensors, additional link demand data for freeway ramps and arterials are also needed. It was mentioned that the FDOT has more data on freeways and some other state roads compared to county and local roads. The MPOs in some cases are supplementing the budget of local public road departments to allow collecting the data in more systematic way.

There is also a need to collect intersection level data including signal timing data and travel time data. Miami-Dade County TPO is collecting signal timing information at the intersection level in a new database. Such data and models can be used for both planning and by traffic operations. The MPO is also trying to increase the network geometry data collection.

The FDOT is gathering data from different sources. Agencies also started collecting pedestrian and bicycle data, some from private sector vendors. This data may be useful for modeling. FDOT is looking at all acquired data by different departments to make full utilization of data and to eliminate duplication. We need to understand what data is needed and how the data can be used for different applications.

It was mentioned that archiving data and network True Shape files need to be centralized. The data collected in a project often cannot be located after the project ends. Turning movement counts is expensive to collect. Currently only the data available from Traffic Online is available. If data is available from other projects, this will reduce the cost and time. Archiving the models developed in previous projects is also useful. However, it should be recognized that usually it takes several years from design to construction, but the FHWA requires to validate the counts if the analysis used in the design are more than three-year-old.

2.3.5 Model Development and Calibration

The idea of multiscenario analysis based on cluster analysis of traffic and event data seems to be attractive to TSMO and traffic engineering study staff. However, planning and design staff things that such analysis may add unacceptable additional cost. Nevertheless, the FTE team expressed interest in at least exploring the use of multiscenario modeling for their applications. The FTE team said that although multiscenario modeling is possibly not needed for some types of analysis. For example, the geometry design changes making detailed analysis like this not useful. It is useful for TSMO and when examining fine-tuning of the build alternative design.

There is an interest in modeling CAVs. However, there is some uncertainty associated with the levels of accuracy a difficulty with such modeling. One of the FTE staff presented a paper at the Transportation Research Board (TRB) Annual Meeting recently about AV modeling from demand side to supply side. The paper found that the impact of CAV on capacity is similar to what is recommended in the new HCM CAV procedures.

O-D estimation using ODME procedures is increasingly used. However, the results from ODME should not make the distribution very different from the seed matrix. For example, if the initial seed demand matrix indicates that the proportion of the demands between O-D pairs is 20%, the demands after the ODME should not be more than 5%-10% different from the seed matrix.

It is interesting that since last year, the department start comparing the volumes measured after the project opening with the volumes predicted by the model. The comparison indicated a difference of 5% to 10%. The travel time measurements have not been compared in a similar manner.

Another important aspect is performance metric identification and how can simulation help with the identified performance measures of the agency. It appears that there has been limited of use of simulation to estimate additional measures like reliability, emission, fuel consumption, and safety. However, for safety, the change in future vehicle-miles traveled (VMT) has been used to estimate the change in crash frequencies due to the difference in the numbers of vehicles on the road.

2.3.6 Training and Community Building

It was reported that there is a large variation between the qualifications of different districts related to simulation analysis, although most of the modeling effort is done in general by consultants. There is a need for a training course to understand the concepts, and a general overview of the inputs and outputs,

Most of the respondents indicated that training on basic concepts is critically needed more that training modelers on the details of creating and calibrating models. Some of the needed concepts can include when to use the simulation vs. analytical procedures like the HCM, what happens when the model is not adequately calibrated, how to set temporal and spatial limits, the importance of latent demands, etc.

Training should differentiate between that for consultants who create the model versus that needed for reviewers. There is a need to have simulation overview course specific to TSM&O modeling. A course may also be needed to provide TSM&O staff with basic knowledge about the need and benefits of using simulation for TSM&O including supporting performance impacts and return on investment estimation. Demand forecasting modelers may need a basic traffic flow module and the microscopic simulation may need a basic demand forecasting module. All of these workshops can be three-hour workshop.

Data science has evolved and can be used to support modeling and forecasting. There may be a need for training on data and associated software such as Python. There is a need to build a user community similar to the Model Task Force and regional user groups of demand forecasting models.

2.3.7 Demand Forecasting

In general, the quality of the estimated demands from demand forecasting models is not sufficient, although this quality varies by region and location within the region. The demand matrix from the forecasting model is used as a seed matrix. However, it is sometimes adjusted based on data from third parties.

The procedure used for future demand forecasting for future conditions have been different for different projects. Some users use the Traffic Forecasting Handbook method, but considerable judgment is made. A lot of time, the demands are estimated based on judgment by looking at the growth rates, demand forecasting models, model results, and combination of the two. Some modelers use the NCHRP 765 procedure. However, again, this use is combined with judgement depends on the project. The modelers sometime use the NCHRP procedure results in combination with the traffic distribution during the peak period, the growth, future land use, select link analysis using significant judgment. The FTE team uses a spreadsheet to assist with this and published a TRB paper on the subject.

2.4 SUMMARY OF THE FINDINGS

This section presents a summary of the findings based on the responses to the survey presented in Section 2 of this document.

2.4.1 Agency Processes and Resources

There is a need to make the business case for using simulation in processes that are currently do not use simulation when it is needed. Proven cost effectiveness of the model level and tool utilization is critical.

When asked whether the simulation models are being generated in-house or consultants, 35% of the public sector respondents to the survey reported that both the development and review are done in-house, 41% reported development by consultants but the review in house, and 24% reported that both the development and review are by consultants. 64% and 88% of the public and private sector respondents, respectively, said that they have sufficient staff to develop and review the model. However, as indicated in the interview results discussed below the above numbers overestimate the public agency capabilities and contribution to model generation. This is possibly because the public sector respondents include their in-house consultants when reporting on the public agency model generation and capabilities.

The simulation models in Florida are mainly developed by consultants. Not all consultants have the capability to develop simulation models, particularly for large works. Some agencies have adopted detailed processes for the review. Others do not have such process. The review process is sometime done by a third party (another consultant) and sometimes by the public agency. In general, experience with reviewing and running the model in the public agency is limited and the review sometimes is limited to checking the consistency and how logical are the model results as reported. The use of a third party for review, although it has been used, adds a significant cost to already expensive modeling efforts. On the other hand, maintaining experts in the simulation in the public agencies can also be very expensive and difficult, particularly with the competition with the private sector on talents in this area.

When asked if the agency archive and maintain the simulation models after the end of the project, 57% of the respondents to the survey said they do archive the model. Some agencies reported that in few cases, they used the same model in more than one project. This helped in the work and saved budget. However, it was mentioned that archiving the models has problems in that in some cases old models may not be compatible with the new version of the software, in addition to maintaining the model current.

The lack of budget affects the calibration quality and the number of alternatives that can be evaluated. Respondents pointed that additional budget is needed to be assigned for software license and training. The adequacy of the budget will be impacted by the introduction of additional modeling requirements such as multiresolution simulation and multiscenario simulation.

2.4.2 Guidance Utilization

About 43% of the respondents to the survey said that they use specific guidance to decide on using simulation versus using other analysis techniques with 28% saying that they use the FDOT Traffic Analysis Handbook for this purpose. The remaining 53% use other methods to make the decision such as deciding based on project's scope, needs, complexity, and level of analysis; consultant recommendation; availability of budget; acceptability to the agency; and the level of congestion.

Only 61% of the respondents said that they use formal guidelines or manuals in the development and calibration of models with 15 respondents using the FDOT procedure for this purpose. Additional guidance topics mentioned as needs by the respondents include the provision of additional information related to data; provision of examples to model certain unique situations; extend the focus to include public transit, pedestrian, bicycle, and other modes of travel; recommending different approaches to modeling depending on the analyzed alternatives; and the provision of additional guidance for mesoscopic modeling and multiresolution modeling. When asked if there is a need for general simulation guidance or tool-specific guidance; 66% said there is a need for both, 25% said that there is a need for general simulation guidelines, and 9% said that there is need for just tool specific guidance.

There was a general agreement that the calibration criteria in the FDOT calibration guidance is good but sometimes discussions are needed to provide justifications if the criteria are not met. One opinion is that the model development and calibration do not have to be rigid. The calibration criteria should be flexible and should not be complex and hard to meet.

Since 2005, the FTE has developed and maintained a detailed internal simulation guidance as a living document. The guidelines are based on current practices and the guidelines of Florida and other states (e.g., Oregon), FHWA volume 3 (2003 version). The guidance is both general and software (Vissim) specific. It add much more detailed step by step guidance to the 2014 FDOT Traffic Analysis Handbook.

A new version of the FDOT Traffic Analysis Handbook has been updated and there is a draft version of the handbook under review by FDOT. This update is expected to be released around May 2021. The updated handbook will include new policies, chapter for modeling of managed lanes, performance measures other than quality of service for alternative comparison. Other sections of the manual were updated to reflect current information, but some sections/chapters have no major changes. CAV and multiresolution modeling will not be addressed in this version.

2.4.3 Analysis Types and Tools

As expected, based on 61 public and private sector responses to the survey, most modelers in Florida use either microscopic simulation or macroscopic analysis procedures and tools like HCM-based analyses and Synchro analyses. However, an interesting finding based on the conducted survey is that about quarter of the respondents use mesoscopic modeling and sometime multiresolution modeling mainly utilizing the Cube Avenue tool. However, the use of multiresolution modeling with DTA and/or mesoscopic by the agencies is in reality limited based on the phone interviews. The microscopic simulation tool with the highest percentage of use is Vissim (81.4% of the respondents), followed by SimTraffic (57.6%), followed by CORSIM (39%). Nine (15.3%) and four (6.8%) of the respondents use TransModeler and Aimsun, respectively. Microsoft Excel appears the tool that is most widely used in conjunction with simulation, although very small proportions of users use other supporting tools.

Microscopic simulation has been used to support the evaluation of various design alternatives. In general, the selection is based on the judgment of the public agency and their consultant. Conditions that usually triggers the use of simulation are closely spaced intersection, high demand to capacity ratios in urban areas, backups between intersections and/or interchanges complex system configuration, express lane use, etc. Look at these factors in combination. All of these factors are looked at in combinations.

In some cases, when using simulation, HCM analyses is performed for initial screening of the alternatives and simulation is used later for more detailed analysis. Simulation using SimTraffic is used in many cases for small projects where such use is adequate in lieu of the using more detailed analysis using software like Vissim or TransModeler analysis. For under-saturated conditions, HCM type of analysis can be adequate. It appears that the degree to which more detailed microscopic simulation models are used vary by FDOT district. The specific type of modeling is usually agreed on for a project and the agreement is documented in a project memorandum of understanding (MOU).

When selecting the tool and analysis type, the ease of use, available expertise, and comfort level with the tool were mentioned as criteria. Some tools require a lot of effort but provide limited additional benefits. The analysis may need three levels of tools with different levels of accuracy for different levels of the decision-making process. There is a need to justify the extra time and expense required for simulation from a return-on-investment point of view. This should be accompanied by a marketing campaign to communicate the benefits

2.4.4 Data Needs

The responses to the survey indicate that the modelers utilize data from different sources. Tube counts and turning movement volume counts is still the main source of volume data. However, only 39% collect heavy vehicle information. ITS detector data is used by about 44% of the respondents. Some users mentioned that in the past used travel time data collected in the field but recently are using third party data. Travel time measurements are still collected using test car studies by about 60% of the participants. However, about the same percentage use Bluetooth readers and about the same percentage use third party vendor data. About 47% use O-D data from the demand models and 47% use O-D data from third party vendors.

Traditional methods of collecting travel time are still widely used. For example, travel time measurements using test cars is used with a minimum specified or calculated number of runs. It was reported that data from third party vendors like HERE and Inrix may be too aggregate in space since the measurement segments have fixed lengths that can be sometime too long.

The FDOT is gathering data from different sources. There is a need to understand what data is needed and how the data can be used for different applications. Although freeway mainline links have sensors, additional link demand data for freeway ramps and arterials are also needed. It was mentioned that the FDOT has more data on freeways and some other state roads compared to county and local roads. The MPOs in some cases are supplementing the budget of Public Road Departments to allow collecting the data in more systematic way. There is also a need to collect intersection level data including signal timing data and travel time data. Agencies also started collecting pedestrian and bicycle data, some from private sector vendors.

There is a concern about data availability, particularly if data is required for multiple weeks and months and particularly for arterial streets. O-D data is also very important and difficult to get. In addition, there is a concern about the uncertainty in the quality and resolution of data from third party vendors. There is also uncertainty about data quality in general and the need for guidance for data quality and data cleaning. There is need for the discussion of usable data and what constitutes useable data by type. A significant consideration is the inconsistency in the data, particularly when collected in different days. Data measured in the same days is needed to ensure that the simulation models are correctly calibrate Data sharing between agencies can be helpful. General calibration data for major highways in each region could be centralized for use in simulation to ensure consistency. The quality of the collected data from third party vendors need to be examined. In some cases, the data shows uncongested locations having congestion and vice versa. Data should be examined by an analyst that is familiar with the area. SunGuide detector volume counts also need examination, particularly with regard to volume counts. It was mentioned that the devices need frequent calibration (e.g., every three months). The data quality is different for different regions.

For better calibration of simulation models, there is a need for more frequent data for special events simulation (multiscenario simulation). There is a need for the expansion of count data locations with more data points throughout the year instead of three-day counts.

It was mentioned that archiving data and network True Shape files need to be centralized. The data collected in a project often cannot be located after the project. Turning movement counts is expensive to collect. Currently only the data available from Traffic Online is available. If data is available from other projects, this will reduce the cost and time. Archiving the models developed in previous projects is also useful. However, it should be recognized that usually it takes several years from design to construction but the FHWA requires to validate the counts if the analysis used in the design are more than three year old.

2.4.5 Model Development and Calibration

A step-by-step guide for calibration will be helpful. It was mentioned that there may be a need to have more flexibility in the calibration and validation requirements depending on the project at hand. The calibration targets may be too rigid and having targets that have ranges may be needed. Avoiding over-fitting of the model to the observed data in the calibration is also important.

There is a need for a clear documentation of the calibration process conducted by the modeling team to allow a better review of the developed simulation model. Guidelines is needed on acceptable ranges for various driving behaviors parameters to use in the simulation tools. In order to determine which field-measured metrics should be used under which circumstances

There is a need to identify the performance measures for use in reporting the results including those that reflect the actual differences in system performance between alternatives and that can be understood by the decision makers. Regarding the measures currently used or needed based on the output of simulation models, the respondents reported that queue length, travel time, and level of service are the most widely used. Interestingly, reliability is ranked fourth after these measures (45.8% of the respondents) as a needed measure followed by the number of Stops. Also, interesting is that about 19 respondents reported the use of emission and safety surrogate measures as needed. However, it appears that there has been limited of use of simulation to estimate additional measures like reliability, emission, fuel consumption, and safety. However, for safety, the change in future vehicle-miles traveled (VMT) has been used to estimate the change in crash frequencies due to the difference in the numbers of vehicles on the road.

The idea of multiscenario analysis based on cluster analysis of traffic and event data seems to be attractive to TSMO and traffic engineering study staff. However, planning and design staff things that such analysis may add unacceptable additional cost. Nevertheless, the FTE team expressed interest in eat least exploring the use of multiscenario modeling for their applications. Advanced users said that although multiscenario modeling is possibly not needed for some types of analysis. Sometime, the geometry design changes making detailed analysis like this nor useful. It is useful for TSMO and when examining fine-tuning of the build alternative design.

There is an interest in modeling Connected Automated Vehicles (CAVs). However, there is some uncertainty associated with the levels of accuracy and difficulty with such modeling. One of the FTE staff presented a paper at the Transportation Research Board (TRB) Annual Meeting recently about AV modeling from demand side to supply side. The paper found that the impact of CAV on capacity is similar to what is recommended in the new CAV procedures of the HCM. O-D estimation using ODME procedures is increasingly used. However, the results from ODME should not make the distribution very different from the seed matrix. For example if the initial seed demand matrix indicates that the proportion of the demands between O-D pairs is 20%, the demands after the ODME should not be more than 5%-10% different

It is interesting that since last year, an FDOT department start comparing the volumes measured after the project opening with the volumes predicted by the model. The comparison indicated a difference of 5% to 10%. The travel time measurements have not been compared in a similar manner.

2.4.6 Training

When asked about the training needs, about 44% of the survey respondents said that there is a need for a general training of simulation modeling. About 10% specified training on specific advanced topics like dynamic traffic assignment, automated output processing, application program interface, and modeling complex intersection and interchange designs. About 20% specified tool specific training.

It was reported that there is a large variation between the qualifications of different districts related to simulation analysis, although most of the modeling effort is done in general by consultants. There is a need for a training course to understand the concepts, and a general overview of the inputs and outputs, Most of the respondents indicated that training on basic concepts is critically needed more that training modelers on the details of creating and calibrating models. Some of the needed concepts can include when to use the simulation vs. analytical procedures like the HC, what happens when the model is not adequately calibrated, how to set temporal and spatial limits, the importance of latent demands.

Training should differentiate between information needed for consultants who create the model versus that needed for reviewers. There is a need to have simulation overview course specific to TSM&O modeling. A course may also be needed to provide TSM&O staff with basic knowledge about the need and benefits of using simulation for TSM&O including supporting performance impacts and return on investment estimation. Demand forecasting modelers may need a basic traffic flow module and the microscopic simulation may need a basic demand forecasting module. All of these workshops can be three hour workshop.

Data science has evolved and can be used to support modeling and forecasting. There may be a need for training on data and associated software such as Python. There is a need to build a user community similar to the Model Task Force and regional user groups of demand forecasting models.

2.4.7 Future Year Demand Forecasting

The respondents believe that the demand forecasting models are not accurate enough to produce accurate traffic demands for simulation modeling, even when peak period models are used. The regional models are unconstrained by capacity. Thus, the model output volumes are higher than capacities and the unmet demands cannot be correctly represented and simulated. In addition, the regional models are not validated at the turning movement volume level for the peak hour (peak 15 minutes are usually needed for the simulation). Demand forecasting models are often too general for the small focus area of the simulation. In addition, the TAZ's definitions and their connections to the network links in the demand models are often too course and can lead to misleading results. Identifying the demand for the shoulder hours and for future years including peak spreading is challenging. One respondents recommended adopting the NCHRP 765 demand forecasting procedure across the state for future demand forecasting. It appears that the quality of the demand models varies by region and location within the region. The demand matrix from the forecasting model, if of a good quality can used as a seed matrix to ODME procedures.

The respondents appear to use different methods to forecast future year demands including using the demand forecasting models, growth rates (based on counts, demand model growths, and a combination of the two), self-developed Excel spreadsheets possibly combined with ODME process, the Florida Project Forecasting Handbook procedure, using tools like TURNS and Matrix Variator (this tool is used for peak spreading), DTA, and NCHRP 765 procedure.

2.4.8 Additional Needs and Issues

About half of the respondents reported that they are interested in the modeling emerging technologies such as connected, automated, and electric vehicles. About 26% are highly to extremely interest in this modeling but half of the respondents are not interested in such modeling at least in this time.

When commenting on the main issues facing their simulation effort, they mentioned the following:

- Not enough internal expertise for coding, running, and interpreting the results
- Training and lack of experience
- Need for DTA guidance
- Need for reliability and scenario-based analysis
- Difficulty in maintaining software and licenses
- The amount data required for a good model
- The time it takes to calibrate a model
- Availability of reviews to ensure that the correct building and calibrating of the models
- How to present the results to the decision makers and what measures to use?
- CV incorporation in practice
- What is the anticipated percentage of emergent technology adoption (market penetration) and the percentage that will provide benefits?

CHAPTER 3: ASSESSMENT AND EXTENSION OF AVAILABLE GUIDANCE

3.1 INTRODUCTION

The Florida Department of Transportation (FDOT)'s Traffic Analysis Handbook provides guidance for use of traffic analyses tools in FDOT projects. The Handbook addresses analytical tools such as Highway Capacity Manual (HCM)-based tools, highway safety manual (HSM)-based tools as well as microscopic simulation (microsimulation) tools. This chapter focuses on providing information not covered or has limited coverage in the handbook including:

- **Representative Day and Multiscenario Analysis**: This section addresses how to select a representative day for the analysis and single analysis vs. multiscenario analysis.

- **Setting Calibration Targets:** This section addresses the simulation calibration targets provided by the FDOT with the targets provided by other state DOTs and national guidance.

- **Estimation of Non-Traditional Measures**: This section discusses estimating measures such as safety performance metrics, sustainability metrics, and travel time reliability metrics based on simulation results.

- **Post Projection Validation:** This section provides recommendations regarding post-project validation is recommended for checking the calibrated model is able to predict the performance of the system after implementing the project improvement.

- **Calibration of Bottleneck Attributes:** This section presents additional information regarding calibrating the performance of traffic bottlenecks, which is one of the most critical aspects of traffic simulation.

- **Automated Data Sources:** This section considers existing and emerging data sources that can be used to support simulation modeling and their strengths and limitations. The discussed data sources include point detectors, Bluetooth and Wi-Fi readers, private sector travel time data, private sector O-D data, high resolution controller data, connected vehicle (CV) and automated vehicle (AV) data, vehicle trajectories, and event data.

- **Data Quality Assurance:** This section discusses the importance of data quality assurance and the procedures used to assure data quality.

- **Traffic Assignment:** This section discusses traffic assignment with focus on dynamic traffic assignment including assignment components, assignment types, generalized cost function formulation, convergence, demand estimation, and zone and connector disaggregation.

- **Multiresolution Modeling:** This section addresses conducting multiresolution analysis including project planning and scoping, performance measure identification, data requirements and availability, model development, and ensuring MRM consistency

- **Modeling of Connected and Automated Vehicles**: This section discussed vehicle connectivity and automation (CAV), CAV modeling framework, identification of the technical approach, uncertainties associated with CAV, performance measure identification, data requirements and availability.

After providing recommendations regarding additional guidance on the topic in the above list. This project researched two of the topics in more detailed. The first is comparing the FDOT calibration targets with other national and state guidance. The second is the selection of representative day(s) for modeling.

3.2 REPRESENTATIVE DAY AND MULTISCENARIO ANALYSIS

Analysts tend to use a single, average day based on data collected from different days of the year for the analysis. This approach is not correct when using simulation models since an average synthetic does not really exist in the real-world. Calibrating a model for a synthetic day is impossible since for example the average traffic demands do not correspond to average travel times. In other cases, a random day during the year is selected for analysis, which does not adequately reflect the demands in the network. Thus, it is important to select a representative day rather than average day for modeling. In addition, the current practice is to exclude days with events such as incidents, weather and unusually high or low travel demand from the calculations. This is acceptable if modeling these days is not important to the analysis. However, in some cases, the modeling of variations in recurrent congestion and the impacts of events is important such as when assessing TSMO, managed lane, congestion pricing, and connected and automated vehicle applications. The FDOT Traffic Analysis Handbook by FDOT (FDOT Systems Planning Office, 2014) provides no information related to using multiscenario and representative days for calibrating a microsimulation model.

During the scoping stage, the project modeling team should specify how to select the representative day(s) for the analysis whether there is a need for multiscenario analysis that model different conditions in the network. Depending on the project scope, multiscenario analysis can be specified to include different levels of recurring congestion and the assessment of the impacts of non-recurring factors such as traffic incidents, weather, work zones, and special events. When considering the use of multiscenario analysis, the analyst can consider the procedure in FHWA Traffic Analysis Toolbox Volume III (Wunderlich et al., 2019), which recommends a cluster analysis to identify operational scenarios and the selection of a representative day for each scenario.

It is recognized that multiresolution impacts the budget, time, and data needed for the analysis. Thus, during the scoping stage, the project team should justify the use of multiscenario analysis. The FHWA Toolbox methodology (Wunderlich et al., 2019) assign days into different clusters, based on the similarity in operational conditions that include demand levels and patterns, travel times, bottleneck throughputs, weather conditions, incident types and other planned disruptions such as work zones and special events. Even, if multiscenario analysis is not used, the analyst can use the method presented in the FHWA Traffic Analysis Toolbox Volume III (Wunderlich et al., 2019) to identify a single representative day for the year, although that method was developed for multiscenario analysis. In this case, weekends and days with events like precipitation, crashes, constructions, and lane closure should be omitted from the collected data and separated, if only “normal days” are to be considered in the selection of the representative day

A later section of this chapter presents an application of the methodology developed in this project to perform cluster analysis to identify the representative day.

3.3 ESTIMATION OF NONTRADITIONAL MEASURES

In addition to the mobility metrics that are the main metrics calculated based on the outputs of the analysis, modeling, and simulation (AMS) tools; there is great interest in efficient and effective methods to estimate reliability, emissions, and safety based on the results of the MRM. Due to the limited outputs from existing tools related to these measures, the calculations of these measures require post processing of the outputs. This section describes the processes used for this purpose.

3.3.1 Safety Performance Metrics

In some projects, improving safety is an important objective. Simulation models do not directly output safety measures like crash frequency, rates, and severity. These models are programmed so that crashes do not occur since microscopic traffic models like the car following models, lane changing models, and gap acceptance models assume safe drivers. In addition, most simulation models do not automatically change driver behaviors as a function of road geometry such as lane and shoulder width and curvatures. When appropriate analysts can estimate crash rates and anticipated changes to these rates using the procedures of the Highway Safety Manual (HSM) (AASHTO, 2010). Analysts can also use demands, operating speeds, and other macroscopic measures estimated from macroscopic, mesoscopic, and microscopic model outputs, as inputs to the safety performance functions, as defined in the HSM and calibrated in Florida, to predict safety for future conditions

However, in many cases, the project improvements cannot be adequately assessed using the HSM. In these cases, the analyst may be able to assess safety using safety surrogate measures (SSM) based on vehicle trajectories. Analysts can use the Surrogate Safety Assessment Model (SSAM) tool developed by the FHWA to estimate surrogate safety measures based on vehicle trajectory outputs from microscopic simulation models (Pu & Joshi, 2008).

Examples of SSM are the probability distribution of headways at the bottleneck locations, the distribution of deceleration rates, the number of lane changes per lane mile, the percentage of lane changes for an exit that occur within *x* feet upstream of the exit, and the frequency of following vehicles being within 2 seconds of a lead vehicle. More information about the selection of SSM can be found in (Gettman & Head, 2003).

The analyst should recognize that safety analysis using simulation may require further calibration and validation of the vehicle trajectories produced from the model. For example, Hadi et al. (2021) developed a method to evaluate the safety benefits of Red-Light Violation Warning (RLVW), a connected vehicle-based application at signalized intersections, utilizing simulation (Hadi et al., 2021a). To accurately model the impacts, the authors had to calibrate the driver behavior in dilemma zone since this behavior contributes significantly to the frequency of red light running. The calibration was done based on a models borrowed from the literature to replicate the real-world drivers' behavior in the dilemma zones. The parameters of the utilized model are best fine-tuned based on local data if such data is available. Such data will become more widely available with the adoption of CV and high-resolution controller data. Figure 3-1 shows the probability of stopping resulting from the simulation model with and without the calibrated coefficients compared to the results expected based on the model derived using real-world drivers' behavior. This figure clearly shows the need to calibrate the model parameters based on real-world conditions to produce acceptable safety analysis.

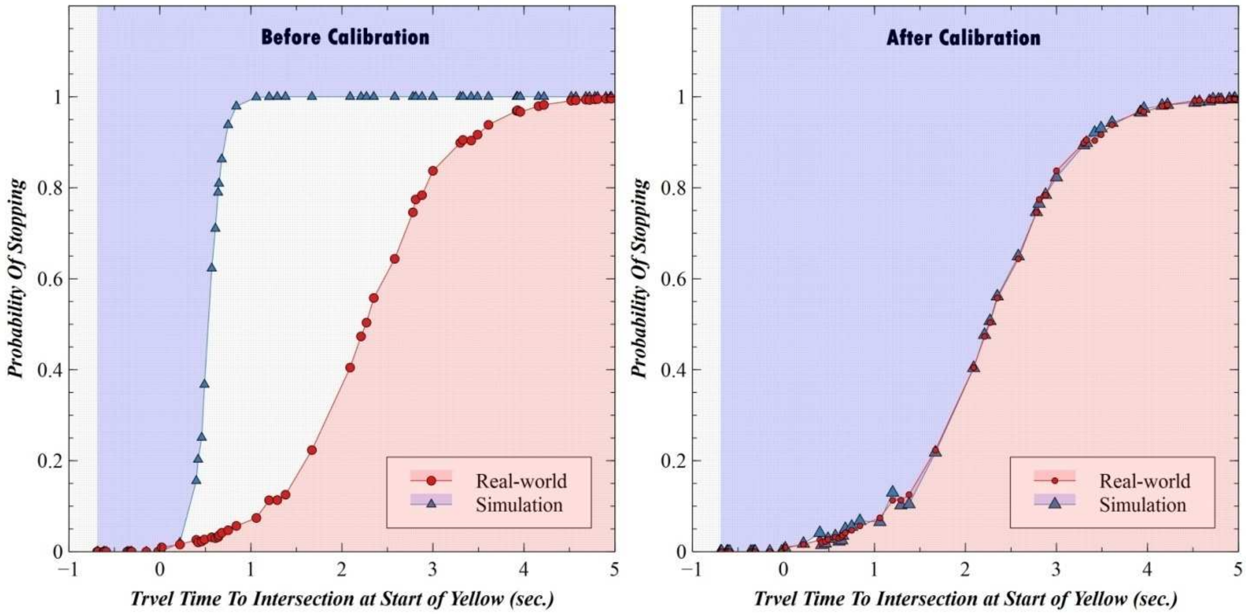


Figure 3-1 Simulation versus real-world probability of stopping

(Hadi et al., 2021a)

3.3.2 Sustainability Metrics

Sustainability metrics such as energy and pollution-related metrics are also important to many projects. Some simulation software packages produce estimates of these metrics. However, when this analysis is important to the project objectives and EPA compliant emission results are required, it is recommended to use more detailed analysis using external tools such as the Motor Vehicle Emission Simulator (MOVES) model, produced by the Environmental Protection Agency (EPA, 2021). If the goal is just to compare the emission level with different alternatives, Washington

DOT Vissim guidance (Schilperoort et al., 2014) states that "with the goal of comparing scenarios, precise methods and output for emissions may not be necessary."

The EPA's MOVES model estimates emissions using three different estimation methods: the average speed approach, drive schedule approach, and operating mode distribution approach. The average speed approach is the simplest of the three and is based on the average speed of the vehicles and the vehicle miles traveled by vehicle type. The drive schedule method uses second-by-second speed profiles of vehicles as an input to estimate emissions. The operating mode distribution approach estimates emissions based on the Vehicle-Specific Power (VSP), vehicle speed, and vehicle acceleration. All three methods can be utilized based on microscopic simulation model outputs. However, if using an emission estimation method that requires vehicle trajectories such as the drive schedule approach, and operating mode distribution approach in MOVES, calibration and validation of the simulated vehicle trajectories is recommended. In the scoping stage, the project team should identify if sustainability measures are to be used, the level of details of the modeling, and the method used in their calculations.

3.3.3 Travel Time Reliability

Agencies have identified travel time reliability as an important measure to assess system performance. It is recognized that many improvements, particularly those related to transportation system management and operations (TSM&O) can have more impacts on travel time reliability than mobility since these strategies involve managing traffic conditions under different levels of demand and special event, incident, work zone and weather conditions. Commonly used reliability measures are included in Table 3-1.

Table 3-1 Definition of reliability performance measures
(Hadi et al., 2014)

Reliability Performance Metric	Definition
Buffer Index (BI)	The difference between the 95th percentile travel time and the average travel time, normalized by the average travel time
Failure/On-Time Performance	Percentage of trips with travel times less than: • 1.1× median travel time • 1.25× median travel time Or percentage of trips with speed less than 50, 45, 40 or 35 mi/h
95th Planning Time Index	95th percentile of the travel time index distribution (95th percentile travel time divided by the free-flow travel time)
80th Percentile Travel Time Index	80th percentile of the travel time index distribution (80th percentile travel time divided by the free-flow travel time)
Skew Statistics	The ratio of 90th percentile travel time minus the median travel time divided by the median travel time minus the 10th travel time percentile
Misery Index	The average of the highest 5% of travel times divided by the free-flow travel time
Probability Density Function of Travel Time Rate	Probability density function of travel time rate distribution
Cumulative Density Function of Travel Time Rate	Cumulative density function of travel time rate distribution
Semi-Variance	The variance of travel time rate (in sec/mi) pegged to the free-flow travel time instead of the mean travel time
Standard Deviation	Usual statistical definition
Kurtosis	Usual statistical definition
Reliability Rating	Percentage of VMT at a TTI less than certain threshold (for example, 1.33 for freeway and 2.5 for urban streets)
Policy Index	Mean travel time divided by travel time at target speed
Semi-Standard Deviation	One-sided standard deviation that is referenced to the free-flow travel time

The estimation of travel time reliability can be done using the same multiscenario analysis procedure under different levels of congestion and causes of that congestion, as discussed earlier. The performance of different scenarios estimated using multiscenario analysis can be then extended to estimate the full-year variations in travel time by applying the probabilities of each scenario occurring over the course of 1 year.

As described in the multiscenario analysis, reliability estimation requires collecting traffic volumes, incident logs, weather reports, special event schedules, and work zone logs for the study area. The reliability estimation based on multiscenario analysis should uses a clustering analysis, such as the one described in the Traffic Analysis Toolbox: Volume III (Wunderlich et al., 2019). Further discussion of a methodology to perform cluster analysis is presented later in this chapter,

3.4 POST-PROJECT VALIDATION

Post-project validation is recommended for checking the calibrated model was able to defensibly predict the performance of the system after implementing the project improvement. The upcoming transportation system simulation manual (TSSM) recommends a process to accomplish this validation. Post-project validation provides the opportunity to improve the quality of the simulation models and analysis efforts of the project since the validation for the project opening year can identify required changes for future year models. In addition, this effort can help inform how analysis practices can be changed in the future. However, it is recognized that the extent of the validation depends on financial constraints.

If post-projection validation is to be done, agencies may want to consider this in the scoping stage. The assessment will require data for post-project conditions and comparing the results with the system's performance predicted by the simulation for those conditions. The simulation model must be re-run for any conditions that have changed since the original modeling effort. If, for example, the demand forecasting step predicted that the demand increases by 5 percent, but the actual increase is 15 percent, then the new simulation runs should reflect these increases.

The TSSM outlined the following steps for the post-project validation process:

1) *Collect data regarding the post-project conditions and performance*
2) *Re-run the simulation model, if necessary*
3) *Compare performance*.
4) *Identify modeling enhancements*.
5) *Identify ways to improve the modeling process*.
6) *Document the findings*. A record of the results of the analysis should be created as well as the actions taken to make changes, and the rationale.

As with the verification, calibration, and validation (VCV) effort conducted as part of the model development process, the TSSM discusses the use of simulation quality metrics (SQM) to indicate whether the simulation model's predictions of the post-project performance are acceptable. SQMs should measure system performance such as flow rates, travel times, capacities, queue lengths, bottleneck discharge rates and attributes, etc.

3.5 CALIBRATION OF BOTTLENECK ATTRIBUTES

One of the most critical aspects of traffic simulation is to correctly model the bottleneck attributes. When modeling the bottleneck attributes, it is recommended to use the attributes defined by the FHWA in the report Traffic Bottlenecks: Identification and Solutions (Hale et al., 2016). The report recommended the use of the spatiotemporal traffic state matrix (STM) for assessing the bottleneck attributes (see Figure 3-2). The STM can be applied to real-world data and model data to allow visual comparison and can be based on any measure such as speed or speed, travel time rate per mile, or density. Figure 3-2 uses three colors to denote low, medium, and heavy congestion but additional categorization can be used. The above-mentioned report defined a number of STM-based performance measure to rank the bottleneck for potential improvements that can be used in the calibration as listed below:

- Duration: The amount of time that breakdown conditions occur.
- Intensity: The relative severity of breakdown that affects travel. This can include any measure used in the STM that reflects the different levels of congestion experienced on roadways. It can be estimated as the proportion of red area within the STM for any given day. The bottleneck rankings on the RITIS website were based on the ‘impact factor,’ which is equivalent to the bottleneck intensity measure but aggregated for all days of the analysis period (e.g. one year).
- Variability: The changes in breakdown conditions that occur on different days or at different times of day. This can be visualized using the Annual reliability matrix (ARM): With this matrix, the daily intensities are plotted left-to-right onto a two-dimensional, X-Y graph. The Y-axis represents the bottleneck intensity value, ranging between 0% and 100%. Individual days are represented along the X-axis, as shown in Figure 3-2.
- Extent: This is the number of system users or components (e.g., roads, bus lines, etc.) that are affected by the breakdown.

The FHWA project developed a Bottleneck Identification (CBI) software tool to allow the visualization and calculation of the bottleneck attributes that can be useful in the calibration.

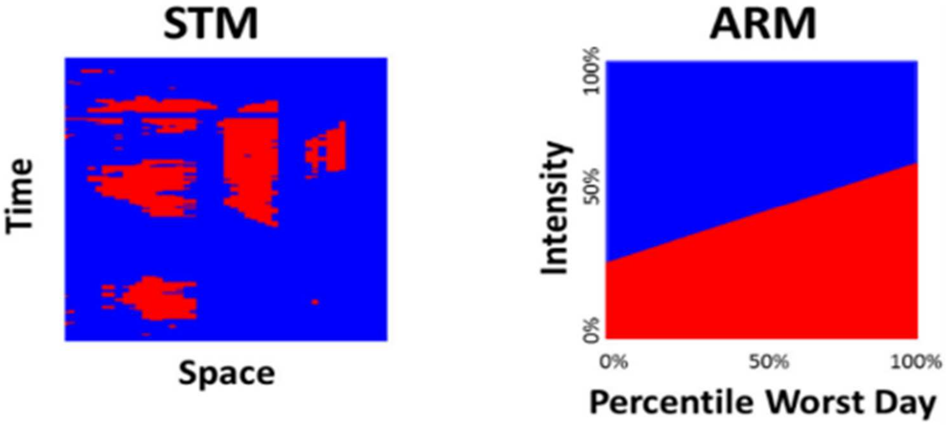


Figure 3-2 Illustrations of spatiotemporal traffic state matrix (STM) concept and annual reliability matrix (ARM)

3.6 AUTOMATED DATA SOURCES

The FDOT Traffic Analysis Handbook (FDOT Systems Planning Office, 2014) provides guidance on the data requirements, data resources and data collection procedures. The Data Collection Chapter has the following chapters: Field Observations, Required Data, Input Parameters Default Values, Data Collection Plan, Existing Data Sources, Data Collection Schedule, Calibration and Validation Data, Quality Assurance. The FDOT Traffic Analyses Handbook has a section about the existing automated data sources. The manual lists the following data sources for:

- Florida Traffic Online (FTO)
- FDOT TRANSTAT Roadway Characteristics Inventory (RCI)
- Straight-Line Diagrams (SLD) of selected RCI data for individual roadways.
- Florida Geographic Data Library (FGDL) (an online portal for distributing spatial data)
- Florida Aerial Photography Archive Collection (APAC)
- Traffic counts from local agency databases.
- Regional Integrated Transportation Information System (RITIS) - which is an automated real time and archiving system
- State and local governments' crash databases.
- State and local governments' signal timing data base

There are additional data types of data that have become available in recent years that can be used to support simulation. There is a need to consider these data sources and their strengths and limitations compared to those of existing data sources. This section discusses various issues associated with existing and emerging data collection technologies.

3.6.1 Point Detectors

The deployment of point detectors has become common on urban freeway facilities as part of the TSM&O program of the FDOT. However, due to cost constraints, the point detection coverage is much lower at rural freeways and urban street midblock locations. There are several types of point detection technologies, each with its strengths and weaknesses. The most commonly utilized technologies are loop detectors, true presence microwave detectors, and video image detectors. The basic parameters that can be measured by these technologies are speed, volume, and occupancy/presence. Space measurements, including travel time, travel time reliability, queue length/back of queue location, density, and shockwave speed have been calculated for freeway segments based on point measurements of the basic parameters. Thus, these space measurements can be less accurate than measurements using devices that provide direct measurements of measurements.

Traffic Volume

Point detectors are currently the most reliable method for traffic volume counts. However, in general, most existing traffic management systems utilize simple methods to estimate travel times based on point measurements. Density has also been estimated using simple methods. The use of the point detector to estimate space measures is not appropriate for urban streets due to the impacts of signals between point detections.

FDOT specifications (FDOT, 2021a) have required minimum accuracy of 95% for volume measurements and provided a method to measure the accuracy based on ground truth data. However, the method calculates the accuracy as one number for the whole day. Minnesota DOT (Minge et al., 2010) study found that four tested non-intrusive detection technology products produced a volume accuracy comparable to loops (typically within 1.6 percent), during both free-flow and congested conditions. However, a per-vehicle analysis revealed some occlusion when slow moving trucks in the lane nearest to the sensor blocked subsequent lanes, resulting in undercounting in periods of heavy congestion with high proportions of trucks. The detectors may also not always be well calibrated for the measurement of volumes. Thus, it is recommended that the modeling community work closely with the FDOT and local agency TSM&O offices to examine and potentially revise the detector accuracy standards and quality assurance practices.

Speed and Travel Time

Point detectors have been used to measure traffic speeds at a point on freeways, and these speeds are then used to estimate the travel times between segments. The speeds and travel times are archived in RITIS. An assessment of speed measurements in Nebraska estimated the speed measurement accuracy to be 95% when testing two widely used true presence microwave detectors, although there may be evidence that this technology may overestimate speeds under congested conditions (Grone, 2012). A Minnesota study found a speed inaccuracy of less than 1 mph of non-intrusive point detection technologies (Minge et al., 2010). A study of dual loop detectors in Arizona showed an average error in 5-minute speed measurements of 6%-7%, with an error range of 3%-12% (Samuelson, 2011). However, one should note that the segment travel times estimated based on these speeds will have higher errors than the speed measurement errors at the point detection locations. This depends on the error in the point detector speed measurements, but also depends on the distances between detectors, the method of segment travel time estimation from point detections, the variations in the congestion conditions between the detection locations, and the speed of the congestion shockwave. Previous research conducted by Hadi et al. based on simulation analysis found that the mean absolute percentage errors were 1.3% and 1.6% for uncongested conditions when the detector spacing was 0.3 and 0.6 of a mile, respectively, if the point detection had a random error of 90% at the point locations (Hadi et al., 2011). The corresponding values for congested conditions during a one-lane blockage incident were about 10% and 20%, respectively. This study also examined the reliability of the estimated travel time, which was defined as the percentage of vehicles with travel times that are within the range of the travel time posted on a traveler's information device. The results showed that 99.75% to 100% of travel time estimates were within the posted travel time range for uncongested conditions, with a detector spacing between 0.3 and 0.6 of a mile, while the reliability of travel time estimates dropped to 54%-74.5% for congested conditions during a one-lane blockage incident.

3.6.2 Bluetooth Readers and Wi-Fi Readers

Bluetooth readers and Wi-Fi readers are classified as automatic vehicle re-identification (AVI) technologies. Examples of other utilized AVI technologies include electronic toll collection and license plate readers, and in-pavement magnetic detectors. Bluetooth and Wi-Fi readers have become the most widely used AVI technology in recent years. These technologies are increasingly being installed for estimating travel time for off-line and real-time applications, particularly on urban streets and, in some cases, on urban and rural freeways. In addition to travel times, AVI technologies have been utilized to estimate origin-destination (O-D) trip matrices, although not all technology vendors provide the data required for this purpose.

Deriving travel times based on point detectors is particularly difficult for urban streets (interrupted facilities). There are a number of challenges when deriving travel times for urban arterials, including lower volumes (thus lower sample sizes), interrupted flow operations that cause variations in travel times in time and space, driveways, and adjacent land uses, and activities that may affect the data collection effort. There has been an increasing interest in the use of automatic vehicle re-identification techniques and third-party vendor data for travel time estimation.

In general, the sample sizes of Bluetooth data, Wi-Fi data, and third-party private sector vendor data are not sufficient for low traffic volume conditions. In addition, the Bluetooth and Wi-Fi readers cannot be placed a short distance apart due to the inaccuracy of the identification of the position of the vehicles within the detection radius. Thus, they cannot be used to determine travel time on short urban street links between intersections.

3.6.3 Private Sector Data Travel Time Data

Private sector data are generally collected from vehicles and/or mobile devices. Sufficient sample sizes of the collected data are necessary to provide the required accuracy. This should not be a problem for urban freeways, particularly in time periods with sufficient demands. However, it could be an issue for some urban streets and rural freeways, particularly in the off-peak periods. There has been a significant increase in the number of tracked devices by the private sector. This trend is expected to continue, resulting in further improvements in the quality of the data. RITIS archives travel times data from HERE for only State Roads in Florida. The national performance management research data set (NPMRDS) is an archived speed and travel time data set obtained and sponsored by FHWA that covers the national highway system (NHS)

It has been reported that travel time estimates from private sector vendors are generally more accurate for urban freeways due to the generally high volumes, which means higher sample sizes, and the lower variations in speed between vehicles. For arterial streets, the accuracy varies depend on the volume, number of intersections per mile, and geometry.

An evaluation of probe data for the I-95 coalition found that third-party probe data can adequately detect congestion on arterial streets when the number of signalized intersections per mile is less than or equal to one on principal arterials with an average annual daily traffic (AADT) of 40,000 vpd or more (Young et al., 2015). However, the study found that the data increasingly underestimates congestion, as the number of intersections increase due to the increase in the variations in travel times and the decrease in volume due to having a smaller sample size than statistically required. Specifically, the study recommended the following:

- Third-party probe data is recommended for use for AADT >40,000 vehicles with two or more lanes in each direction, one or less signal per mile, and limited curb cuts.
- Utilization of probe data should be examined for AADT between 20,000 and 40,000, with two or more lanes in each direction and one to two signals per mile since the results showed that the estimates for some segments were good and for others were not good.
- Probe data are not recommended and the use of vehicle re-identification technology such as Bluetooth readers is recommended for AADT less than 20,000 vehicles per day and more than or equal to two signals per mile.

A study for FDOT (Cambridge Systematics Inc. & Kittelson & Associates, 2015) suggested that although field-measured data are quality checked by the data vendor, additional data quality check should be done. The project team designed the following data quality checks criteria to detect major data errors.

- "Tukey Method: Rank all travel times for a section and treat any value greater than the 75th percentile plus 1.5 times the interquartile distance, or less than the 25th percentile minus 1.5 times the inter-quartile distance as an outlier. This technique is robust because it uses the quartile values instead of variance to describe the spread of the data.
- Two consecutive travel times cannot change more than 40%.
- If a travel time is more than one standard deviation above or below the moving average of the 10 previous entries, the travel time will be removed. Statistics will be gathered on all five-minute records and these values will be aggregated to hourly records to use as the inputs for the MPM database. Volume and speed will have a "completeness" factor to indicate the percentage of valid values used in the aggregate calculation. A value of 1.0 indicates that all records are good. A value >= 0 and < 1.0 indicates that some records are bad or missing, if records are removed missing data strategies described in previous sections will be applied to fill data gaps."

3.6.4 Private Sector Data O-D Data

There has been an increasing interest in using origin-destination (O-D) matrices provided by private sector vendors, either by themselves or in combination with other data sources and demand forecasting model estimates, as inputs to simulation models that require traffic assignment. These metrics are generally calculated based on data points sampled from smartphone applications and global positioning services (GPS) devices. Some vendors provide data that can be used to confirm the traffic assignment results.

The provided data generally includes the relative level of trips between origins and destinations rather than the absolute values of travel time. Thus, the provided values need to be scaled so that it represents the number of trips from an origin to a destination.

Despite the great interest, there has been a concern that the O-D data obtained from third party vendors are subject to potential bias and coverage issues. A Virginia DOT study was conducted to understand the data quality and large percentage errors were often found to be associated with lower volume levels (Yang et al., 2020). The study found using the measures from short travel time periods for estimating the traffic measures resulted in larger errors and that the aggregation of data from multi-periods reduce the errors, due to the increased sample size, especially for low volume conditions. In addition, studies have recommended combining the data with data from other sources such as Bluetooth readers, data from other vendors, and survey results. The study concluded that data accuracy is an issue under low volume conditions (e.g., AADT under 20,000, volume under 500 vph). The study also recommends using benchmark data and calibration procedures of the data. The study recommended aggregating the data for the whole peak period and also aggregating based on metrics of multiple days, weeks, or months. The above mentioned study (Yang et al., 2020) concluded with the following guidance:

- The expected error depends on the demand between each OD pair. Higher demand (e.g., >600 trips/hour) tends to have lower absolute percentage errors (less than 25%).
- Lower demand is likely to have greater absolute percentage errors (higher than 50%) due to the low sampled trips between the zones.
- Some OD pairs may not have observed samples and therefore the estimation is subject to error. (See [G6])
- The route choice analysis cannot be conducted for short-term studies (e.g., 15 minutes, 30 minutes, etc.).

3.6.5 High Resolution Controller Data

In recent years, there has been an interest in Automated Traffic Signal Performance Measures (ATSPM) using data from multiple sources. An important component of ATSPM is the utilization of high-resolution controller data that includes signal timing and detection at the highest time resolution of the controller (0.1 seconds). This data consists of various signal controller events that are logged in 0.1-s intervals based on a standardized set of event parameters and event identification codes The high-resolution controller data can provide significant support of simulation model calibration and validation by allowing the identification of metrics such as capacity utilization level, progression quality, and estimating performance measures such as volume, delay, and queue length. The Florida Department of Transportation (FDOT) adopted an ATSPM software that was originally developed by Utah Department of Transportation (UDOT). Transportation management agencies in Florida have used this tool and other commercially available tools for ATSPM.

High resolution controller data is particularly useful for applications that require detailed examination of the performance and impacts of signal control. Below is a brief description of the measures that can be obtained based on these data.

Capacity Utilization Performance Measures: The capacity utilization measures are reported for each intersection movement to allow the assessment of the adequacy of the cycle length and green split assignment in accommodating demands. These measures are derived based on three basic measurements: cycle length (C) and green times (G), turning movement counts, and occupancy measurements. Examples of such derived measures for each movement include the g/C ratio (phase split) distribution, phase termination per type (gap-out, max-out, forced-off, and omitted), phase duration distribution, number of phase activations and percentage of cycles with the phase activated, cycle time by time-of-day, volume/capacity (v/c) ratio, green to occupancy ratio (GOR), approach delay, queue length, Purdue phase termination, split failure, yellow and red actuations, and delay and queue estimation

Progression Quality Performance Measures: These are measures that are related to the progression of main street movements that affect the delays and numbers of stops of these movements. These measures include arrival on green, arrival on red, Purdue Coordination Diagram, Flow Profile Diagram (FPD), the platoon ratio (rap) and arrival type (at). The last two measures are progression quality measures that are defined in the Highway Capacity Manual (HCM).

Multi-Modal Measures: This includes pedestrian push button measures including collect the wait time of pedestrians from the time that the button is pushed to the time that the pedestrian phase is served and **p**reemption and priority statistics.

Hadi et al. (2021) developed and demonstrated an advanced method for the calibration and validation of microscopic simulation models of arterial networks utilizing measures based on high-resolution controller data combined with a two-level unsupervised clustering technique for scenario identifications and multi-objective optimization for simulation model calibration identification (Hadi et al., 2021b). The utilized measures are vehicle throughput, green occupancy ratio, split utilization ratio, and percentage arrival on green in each cycle, in combination with other commonly used measures like vehicle travel time and throughput.

3.6.6 Connected Vehicle (CV) and Automated Vehicle (AV) Data

Connected vehicle data are generated from vehicles are transmitted using connected vehicle messages utilizing dedicated cellular communication (C-V2X) or short-range communication (DSRC). The connected vehicle (CV) message types and components are specified in the Society of Automotive Engineers (SAE) J2735 standards (SAE-International, 2016). The basic safety message (BSM), specified in J2735, contains vehicle safety-related information broadcasted to surrounding vehicles, but can be also sent and/or captured by the infrastructure. The BSM, as defined in the J2735 standards, consists of two parts. Part 1 is sent in every BSM message broadcasted 10 times per second. It contains core data elements, including vehicle position, heading, speed, acceleration, steering wheel angle, and vehicle size. BSM Part 2 consists of a large set of optional elements such as precipitation, air temperature, wiper status, light status, road coefficient of friction, Antilock Brake System (ABS) activation, Traction Control System (TCS) activation, and vehicle type. However, a large proportion of these parameters are currently unavailable from every vehicle, and they are not expected to be available. Connected vehicle data can be captured by a roadside unit or can be sent to the cloud for processing and use.

Autonomous vehicles data and connected automated vehicle data can provide additional data items. Some of this data as well as manual driven data are captured by the Car OEMs, and it is possible that the OEMS will share measures or aggregated data with agencies.

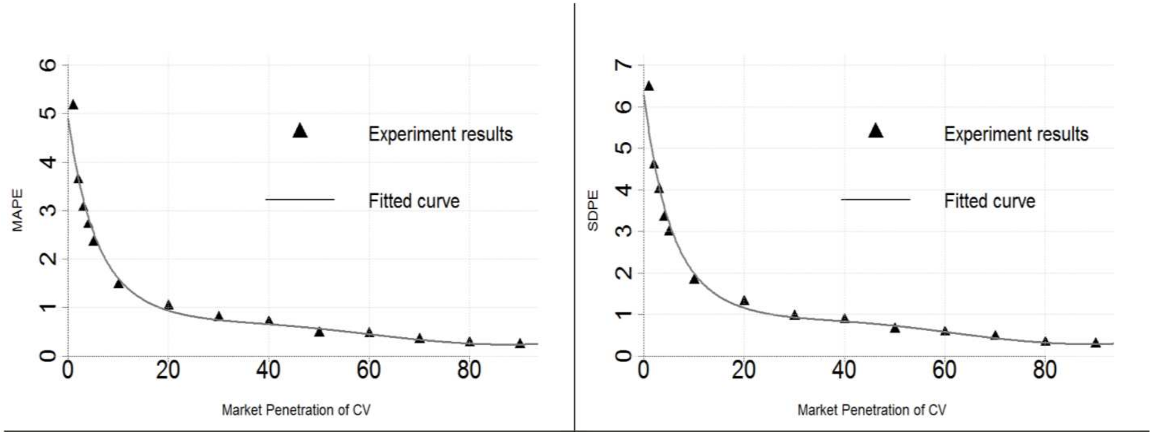
Some of the measures that can be estimated using CV and AV data includes travel time, origin-destination, vehicle classification, Queue length/back of queue, stops, accelerations and decelerations, standards deviations of speeds, intersection movement-level delays and queues, near-misses, emission, and route choice.

As the market penetration of CV technologies increases, the data quality will increase due to the increased sample size. However, it should be mentioned that the requirements that the sample size for planning level analysis can be lower than that required for planning level analysis. This is because the travel time measurements can be accumulated over a number of days.

Zou et al. used simulation to estimate travel time based on CV and found an average error percentage of 27.6%, 12.5%, and 8.2% for 1%, 5%, and 10% market penetrations, respectively (Zou et al., 2010). Hadi et al. assessed the quality of travel time estimates based on CV data on freeway and urban street segments (Hadi et al., 2018). The data quality was investigated under different market penetration scenarios. Figure 3-3 and Figure 3-4 show the Mean Absolute Percentage Error (MAPE), the Standard Deviation of Percentage Error (SDPE), 85th percentile error percentage, and 95th percentile absolute error for freeway and urban streets, respectively. The MAPE is the average error of all days. The MAPE is useful when assessing the average accuracy and is appropriate for using data for planning purposes. The SDPE is a measure of reliability of travel time estimates with higher values, indicating a higher variability in the quality of the data. The 85th and 95th percentile errors are especially useful for real-time utilization of the data and when modeling individual days, as recommended earlier in this document. At market penetrations as low as 1% or lower for the investigated freeway segment and 3-4% for the arterial segment, the analysis shows acceptable MAPE values, indicating that the use of average values over multiple days is acceptable at lower market penetrations. However, larger errors can be observed when examining the 95% or 85% error. For a high demand freeway segment, a low market penetration (1%-2%) is generally sufficient to produce an error that is lower than 10%. For the urban street segments, however, this data quality cannot be achieved until the market penetration of CV exceeds 10%-15%. It should be noted that these results can be different for segments with different demands and configurations, particularly with regard to the congestion level and average spacing of intersections on the urban street segments.

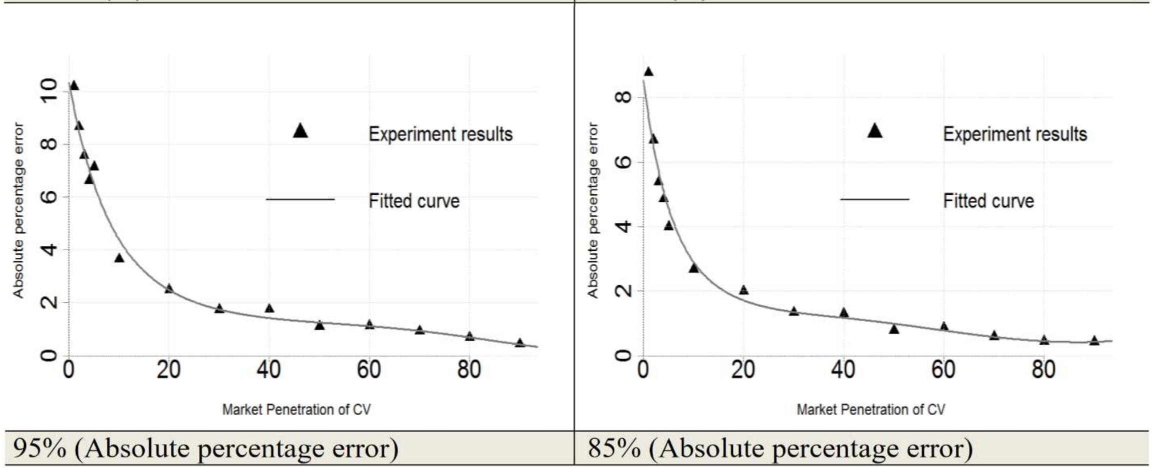
Hadi et al. examined the use of detailed metrics in combination with the usually used macroscopic metrics for the estimation of traffic safety and mobility (Hadi & Azizi, 2020). The utilized disturbance metrics are the standard deviation of speed between vehicles, standard deviation of speed of individual vehicles, acceleration, jerk rate, number of oscillations and a measure of disturbance durations in terms of the time exposed time–to–collision (TET). The authors used data clustering for better off-line categorization of the traffic states. These measures can be used in the calibration and validation of simulation models.

The FDOT has initiated a project to develop V2X Data Exchange Platform that collect and ingest all data generated from CAV projects; TSM&O data from existing freeway management systems, arterial management systems, and commercial vehicle and freight management systems; The platform also includes application program interfaces (API), as needed, to ingest data from other systems into the V2X data exchange. The platform includes data storage, security, normalization, filtering, and aggregation modules. This platform is expected to be a major source of data for the modeling community.



MAPE (%)

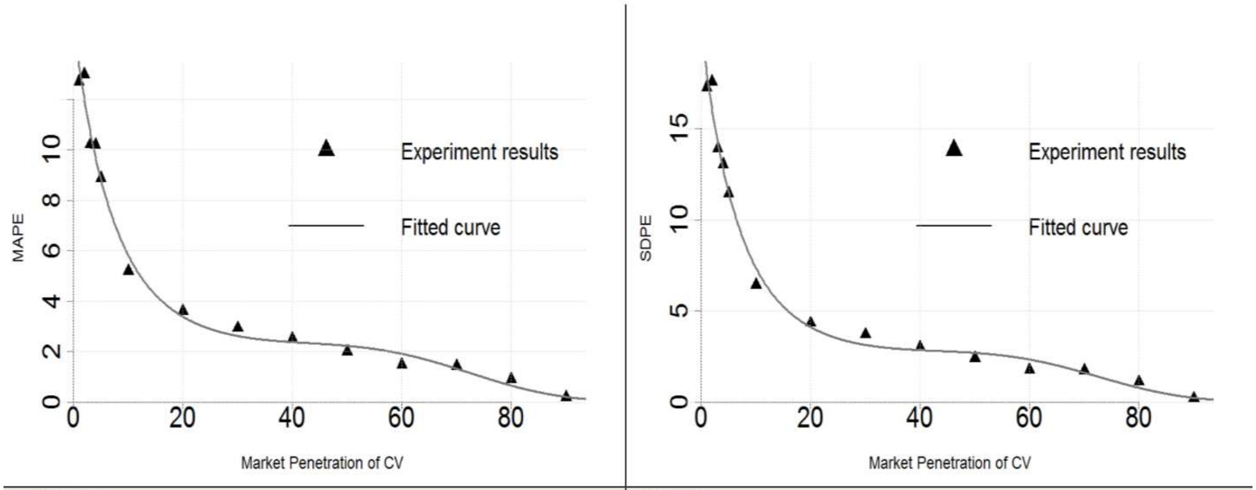
SDPE (%)



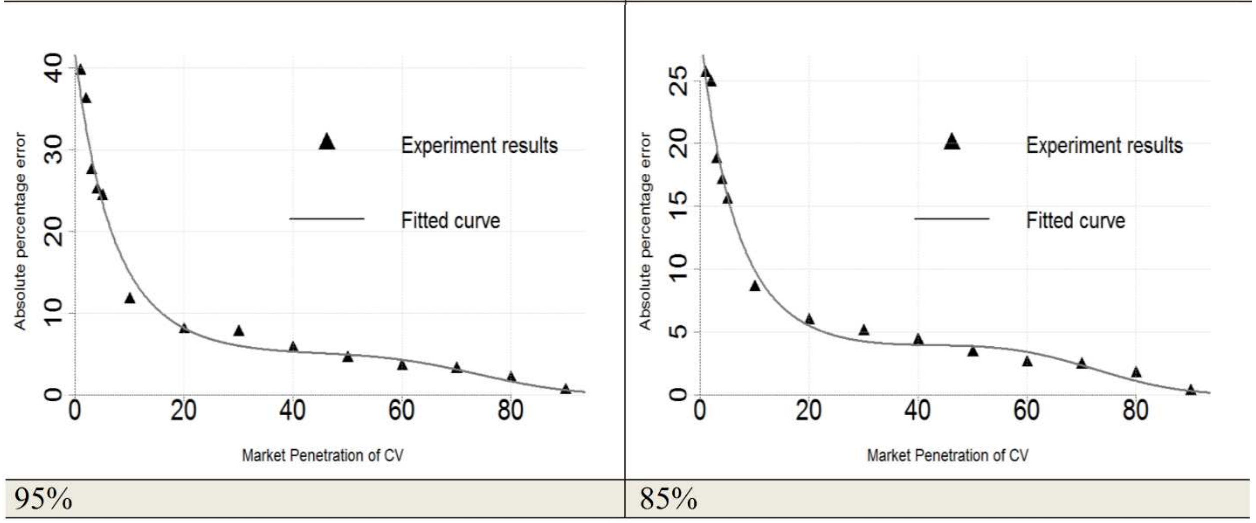
95% (Absolute percentage error)

85% (Absolute percentage error)

Figure 3-3 MAPE, SDPE, 85th percentile, & 95th percentile of a freeway segment (Hadi et al., 2018)



MAPE SDPE



95% 85%

Figure 3-4 MAPE, SDPE, 85th percentile, & 95th percentile of an arterial segment (Hadi et al., 2018)

3.6.7 Vehicle Trajectories

Trajectory data is time-stamped location data that can be collected from instrumented vehicles, emerging infrastructure sensors such as video image sensors that are able to track and report vehicle trajectories, and drones that are equipped with cameras allowing the use of video image detectors to process the data.

Microscopic simulation models use microscopic traffic parameters such as headways, reaction time, acceleration/deceleration, and gap acceptance in modeling traffic flow. However, due to the difficulty and the high cost associated with the collection of microscopic measures, simulation model calibration and validation have mainly been based on macroscopic measures such as capacity, travel time, and queue lengths. This calibration is adequate for most applications of simulation modeling. However, in some cases, it is preferred to do calibration based on microscopic measures. Calibration based on trajectories are particularly beneficial in cases that have complex weaving and merging sections, cases that require estimating safety and emission impacts, and some connected and automated vehicles applications.

Trajectory data can be obtained from unmanned aerial vehicles (drones) that can carry cameras, are equipped with cameras. The recorded videos can be then post-processed to obtain trajectory data information. Vendors are currently available to process the collected videos to produce various measures.

A FHWA project has recently address the benefits of validation in addition to calibration, importance of using fine-grained measures for microsimulation, importance of cost effective technologies to collect full-set trajectory data, and importance and benefits of understanding the trajectory calibration method (Hale, 2020). It was determined that collected longer trajectories by helicopter (trajectory length approximately 1.2 mile) produced better results than using modest improvement where short trajectories were collected by drones (trajectory length approximately 800 ft). However, it was recognized that helicopter data collection unlikely to be cost effective for agencies. Another option for data collection is to use data from instrumented vehicles.

The above-mentioned project identified the following steps to use trajectory data in the calibration:

- Selection of input parameters to be calibrated including those associated with car-following and lane-changing models

- Choosing initial candidate values for each of the selected car-following and lane-changing parameters

- Selecting the output parameters that need to be used in the optimization – the study selected headways and lane utilization as variables in the calibration objective function

- Selecting the number of points per trajectory to include in the analysis, categorize the trajectories into different bins for use in the comparison

- Optimizing the parameters using a heuristic search method based on measures of effectiveness (MOEs) to get a close match between simulated and field observed MOEs.

The final report of the above-mentioned project is not yet available, but information has been provided in webinar presentations. Further details will be presented when the final report becomes available.

Below are examples of driver-based characteristics that can potentially be calibrated based on vehicle trajectories (Hale, 2020).

- Free-flow speed.

- Start-up lost time.

- Desired headway between vehicles.

- Time required to make a lane change.
- Distance required to make a lane change.
- Acceptable gaps for permissive left turns and right turns on red.
- Willingness to cooperate with other drivers (e.g., when blocking an intersection).

3.6.8 Event Data

Event data are important to simulation modeling since they allow the categorization of days according to event occurrence in addition to traffic conditions. If a single "normal" day scenario is used, the data can be used to remove the event days from the analysis. If multiscenario analysis is to be used, then the event data will be used as input to the clustering.

Incidents can be crashes as well as other random events that lead to lane and/or shoulder blockages. The FDOT has detailed incident data mainly on the limited access facilities (freeways) that are covered by the FDOT incident management program. The FDOT regional traffic management centers maintain detailed incident information. This database is updated to RITIS for archiving. The data includes the event time stamps (e.g., time stamps, detection, notification, responder arrivals, and responder departures), incident ID, responding agencies, incident type, incident location, whether the event involves rollover, fire or HAZMAT; and environmental and roadway conditions.

Although the FDOT incident database is very detailed, it is not generally available for facility types other than freeways. For other facilities, analysts can use incident information stored in Signal Four Analytics, a traffic crash database environment developed for the Florida Highway Patrol (FHP). Currently, this program gathers information from FHP reports on a daily basis. Crash occurrence time, location, severity, weather, and pavement conditions are archived in the database. This database provides incident information that is not available in the SunGuide incident management database. However, the Signal Four Analytics system does not provide information such as detailed time stamps of the incident and lane blockage information. In addition, it does not include data for facilities not managed by the FHP.

Another type of event data is weather data. Weather data should be retrieved from quality-controlled local climatological database such that of the National Climatic Data Center (NCDC). This weather data includes the detailed temperature and precipitations information. Construction data should also be examined. Such data are usually available as part of the FDOT incident management database mentioned above. Although transportation agencies have construction and maintenance databases, unfortunately in many cases these databases do not include the timestamps for the actual lane blockages due to construction.

3.7 DATA QUALITY

The FDOT Manual emphasizes the quality of the data used for simulation. The FDOT Manual indicated that when inputting data for microscopic simulation, small errors could lead to amplification errors resulting in a model that cannot be calibrated. The manual recommends checking the collected data for completeness, accuracy, and reasonableness. The manual suggested that the analyst verifies the reliability of the data collected by examining their trends and descriptive statistics and mentioned that statistics such as the mean and standard deviation are useful in assessing the accuracy and precision of the measurements. Another suggested method is to examine the variation of data in time and space to determine data discrepancy or missing data identifying any abnormalities or outliers (and determining their probable causes). The manual also points to the need for the verification should include checking that weather, incidents or construction did not influence the data collected. Additionally, recommendation setting a 10% accepted difference when comparing the maximum traffic count should be compared with the capacity of the facility and travel time data. The recommended quality assurance also includes checking and verifying that the hourly traffic volumes are balanced with a 10% difference between upstream and downstream counts for location with no known traffic sources or sinks. However, the manual does not provide procedures for the above suggestions and does not define the quality measures such as accuracy and precision were not defined.

The TSSM defines data quality measures for use as part of simulation development efforts including data accuracy, latency, and availability, breadth of coverage in space and time confidence data, and depth of coverage (the resolution in space and time that the data items are collected). Other than mentioning the above, the remaining discussion in the TSSM, referenced other documents including the FHWA report by Wunderlich at al. on Scoping and Conducting Data-Driven 21st Century Transportation System Analyses (Wunderlich et al., 2017). That document recommended to focus quality control procedures on the errors that are most likely to impact the model. The TSSM also noted that both Wunderlich et al. and Virginia DOT suggest the analyst should preserve outlier data to capture the variability in traffic conditions (Wunderlich et al., 2017). This is interesting since it seems to contradict the FDOT guidance in removing outliers, although both guidance did not provide a definition of outliers. The TSSM stated that it is important to preserve outliers that are determined to be not due to sensor and processing errors to determine the full range of transportation system conditions.

Wunderlich et al. suggested that it is possible to have significant temporal and spatial inconsistencies in the data even when this data has already been checked before archiving in a data archive (Wunderlich et al., 2017). Thus, inconsistencies in the data should be carefully checked by the analyst. Data requirements, availability, quality, consistency, and filling the data gaps are critical considerations in the planning and when scoping the project and selecting the modeling approach for the project (Wunderlich et al., 2017). Analysts should develop a detailed data plan at the planning stage that includes data quality checking procedures as a critical component of the data plan.

Although, the FDOT Traffic Analysis Handbook (FDOT forthcoming) provides guidance on the data requirements, data resources and data collection procedures. The manual has a small section on data quality assurance, the discussion in that section is limited. As the use of data collected from automated data sources increase, more detailed consideration of data quality is needed. It should be mentioned that the FHWA Toolbox Volume III and the Transportation System Simulation Manual (TSSM) does not address these two issues adequately. This section is to provide information regarding data quality assurance for simulation modeling. Additional research will be conducted in this project regarding data quality and associated impacts on simulation modeling.

3.7.1 Data Quality Metrics

The following measures have been recommended for use to assess the quality of data (Cambridge Systematics 2015). There are no criteria available in the literature to determine the acceptable

Data Accuracy – Defined as the degree of agreement between a data value or set of values and a source assumed to be correct.

Completeness – This measure, also referred to as “availability,” measures how much data is available, compared to how much data should be available, and is typically described in terms of percentages or number of data values. Completeness can refer to both the temporal and spatial data availability.

***Validity* –** This measure can be expressed as the percentage of data values that pass or fail data validity checks.

***Timeliness* –** This measure, sometimes referred to as “latency,” reflects the latency that the data is provided at the time required. Since most simulation analysis is done in off-line environment, this measure is not relevant to the discussion in this document.

***Coverage* –** The degree to which a sample of the data accurately represents the whole population.

***Accessibility* –** This measure reflects the relative ease with which data can be retrieved and manipulated by data users.

Most of the existing automated data collection and traffic monitoring activities are done for applications other than simulation management such as traffic management. It should be recognized that the requirements for the data quality for traffic management can be different from those for AMS. Examples of measures used in assessing data quality are given in Table 3-2.

Table 3-2 Examples of data quality measures (Hadi & Azizi, 2020)

Name	Description	Equation
Mean Absolute Percent Error (MAPE)	Average absolute percentage difference between the estimate and ground truth	$\frac{1}{n}\sum_{i}^{n} \left\lvert\frac{y_i - y}{y_i}\right\rvert$
Mean Absolute Deviation (MAD)/Mean Absolute Error	Average of errors	$\frac{1}{n}\sum_{i}^{n} \lvert y_i - y\rvert$
Root Mean Squared Error (RSME)	Square root of the average of the squared error	$\sqrt{\frac{1}{n}\sum_{i}^{n} (y_i - y)^2}$
The Standard Deviation of Percentage Error (SDPE)	Square root of the average of the squared percentage errors	$\sqrt{\frac{1}{n-1}\left(\sum_{i}^{n} w_i^2 - n\overline{w}^2\right)}$; $w_i = \frac{y_i - y}{y_i}$
* y_i is the estimated travel time of the ith iteration, y is the ground truth travel time, n is the total number of iterations and $\overline{w}$ is the average of all the w_i		

Tarnoff et al. studied acceptable travel time accuracy ranges for different transportation applications (Tarnoff et al., 2008). For travel time information application, it recommended an error range of travel time between 10% and 20%. The study found that the public loses confidence in the distributed travel time when the travel time information has an error exceeding 20%, while a decrease in travel time error below the specified range does not necessarily produce additional benefits. This study also recommended an error range of 5% to 10% in travel time for traffic engineering and traffic management applications, and a range of 5% to 15% for any type of transportation planning applications or long-range monitoring activities. Samuelson recommended the target values in Table 3-3 when assessing the quality of point detectors in Arizona (Samuelson, 2011). The recommended accuracy was a Mean Absolute Percentage Error (MAPE) of less than 5% for speed and less than 10% for volume.

Table 3-3 Target data quality recommended in Arizona study (Samuelson, 2011)

Data Quality	Measure	Target Values
Accuracy	Speed	5% MAPE
	Counts	10% MAPE
Completeness		<20% missing data
Validity	From all detectors	85% valid
	From valid detectors only	90% valid
Timeliness	Accuracy	< 5-minute lag
	Availability	3 years of data
Coverage	Density	< 1.5 mile spacing
	Extent	60% of facility
Accessibility	Time required	unspecified
	Qualitative features	

FDOT Standard Specifications for Road & Bridge Construction specifies traffic detection accuracy of 95% for volume, 90% for occupancy, and 90% for speed for all lanes, up to the maximum number of lanes that the device can monitor as specified by the manufacturer (FDOT, 2021a). For travel time measurements based on probe vehicles, like those based on Bluetooth readers or from third party vendors, the specification requires ensuring probe data detection systems with matching of upstream and downstream detection of the same vehicle at a minimum match rate of 5% with a minimum total roadway segment speed and travel time accuracy level of 90% The specification requires conformance with the accuracy requirements by performing evaluations by comparing sample data collected from the vehicle detection system with ground truth data collected during the same time by human observation or by another method approved by the Engineer. However, the specification provides a method for the calculation of the error in Section 995-2.8.1 that uses the weighted average of the error over the whole day. This method seems to be inadequate since it is expected that the main issue with measurements are in the congested peak period and averaging for the whole day will dilute any error during the peak.

3.7.2 Data Filtering

Although automated data archiving systems such as RITIS include data filtering techniques, it is important to understand data filtering methods and possibly use them to determine the quality of the data. Hadi et al. recommended a rule-based data filtering procedure include the following steps (Hadi et al., 2011):

- Identification of duplicate data records.
- A univariate test to check whether the values of individual traffic parameters exceed predefined.
- Minimum or maximum thresholds.
- A multivariate test of data measurements to check for unreasonable combinations of traffic parameter values such as a combination of zero speed, zero occupancy, and non-zero volume values.
- A temporal variability check to test for constant values of speed, volume, and occupancy for a long period of time, including all zeros, or illogical changes in values.
- Multivariate tests for the average effective vehicle length and maximum density at the temporal aggregation level under consideration based on traffic flow theory equations.
- A spatial check for the relative differences in traffic parameters between detectors at neighboring stations.

3.8 TRAFFIC ASSIGNMENT

Traffic assignment is a critical component of travel demand forecasting models and transportation system analysis. It can be defined as the allocation of trip-based or activity-based demands to transportation network routes to produce a set of link flows, by considering various factors that affect traveler's route choice.

3.8.1 Assignment Components

Traffic assignments can be categorized into static and dynamic assignments. Static assignment assumes that link flows and link travel times remain constant over the modeling horizon. In dynamic traffic assignment (DTA) models, the link flows and link travel times are time-variant. More detailed discussion of DTA components and procedures can be found in Hadi et al. (Hadi et al., 2014).

Existing demand forecasting models, including those associated with the Florida Standard Urban Transportation Model Structure (FSUTMS), use static traffic assignment as part of the travel demand forecasting process. DTA can provide a more realistic representation of traveler behaviors and traffic conditions and provides a better approach for assigning traffic and estimating travel cost and time, thus supporting better demand and performance measure forecasting. This is particularly important for congested networks and applications that are expected to influence strategies driving behaviors such as TSMO, managed lanes, congestion pricing, and work zone applications.

STA and DTA share basic concepts with the basic components of the assignment are listed below with the difference is that these components in the DTA are time-variant, meaning that the resulting estimates vary during the modeled period.

- Path identification between each origin and destination: This step involves the identification of a set of attractive paths between each O-D pair in the system

- Assignment of trip demands to the identified paths: This step involves the assignment of the trip demands to the identified paths in the TDSP step

- Network loading: This component refers to the representation of the movement of vehicles in the network as they travel from their origins to destinations

In DTA models, analysts can classify network loading procedures as analytical procedures or simulation procedures. Due to the complexity of traffic operations, particularly with the presence of congestion and traffic control, simulation-based procedures are the most widely used at the present time. A number of tools have been developed to perform DTA. These tools vary in their capabilities and in the models and procedures used in these tools. For example, the PTV platform has a macroscopic-based analytical DTA and mesoscopic simulation DTA in VISUM, in addition to microscopic simulation based DTA in Vissim. It is recommended to use mesoscopic simulation-based assignment in the case of congested conditions.

3.8.2 Assignment Types

Three different types of DTA have been implemented in DTA tools: non-iterative (sometimes referred to as one-shot dynamic assignment), dynamic user equilibrium (iterative) assignment (UE assignment), and system optimal (iterative). Although most applications will use dynamic UE assignment, the user may consider using the other two methods as needed. UE assignment is the most widely used and it follows the equilibrium assumption of equal travel times on the utilized routes between each O-D pair for all travelers who leave their origins in the same time interval. It should be recognized that equilibrium emulates the long-term selection of drivers of their routes assuming that they are familiar with the recurrent congestion in the network. The assumptions associated with UE are not valid under all conditions. Non-iterative assignment, at least of portion of the demands may be used to assign the demands in one iteration, without achieving equilibrium, to model diversions due to short-term work zones and incidents and to model unfamiliar travelers such as tourists. However, with the advancement of advanced traveler information apps, such distinction may not be as important as it used to be.

Another categorization of DTA assignment types is pre-trip versus en-route assignment. Pre-trip assignment is to model travelers who select their routes before departure. En-route assignment is to consider traveler's adjustment of their routes during their trips based on information received about unexpected conditions such as incidents.

3.8.3 Generalized Cost Function Formulation

Assignment is based on the assumption that drivers select the paths to their destinations to minimize their generalized costs or disutility. The most widely used factor that is considered to impact traveler behaviors in assignment is travel time, and in some cases monetary costs such as tolls. However, other factors such as distances, number of turns, and number of signalized intersections. Biases towards using specific types of facilities such as freeways can be also used. It is possible to include travel time reliability as part of the assignment objective functions. Hadi et al. utilized a simple equation to estimate reliability for use in DTA (Hadi et al., 2016). The analyst should examine objective function settings used in the assignment, and the weights assigned to factors used in the objective function. The weights may change between user groups based on socioeconomic factors, access to information, and onboard equipment. For example, high-income travelers are more willing to pay for alternatives with lower travel times, even when charged with higher costs.

3.8.4 Convergence

UE is achieved when travelers cannot improve their travel times by selecting alternate paths, given their departure time. This implies that every used path between an origin and destination is a minimum cost path and that there are no changes in flow pattern or experienced travel time between assignment iterations after the convergence is approached. Convergence of user equilibrium assignment is necessary to ensure the integrity and stability of the resulting solution and to ensure that the model can be used in assessing alternative designs and operational strategies. Thus, the assessment of convergence is an important step in traffic assignment.

The quality of the assignment is assessed by using a variable referred to as the relative gap. With simulation based DTA usually, it is usually difficult to achieve relative gaps as low as those required for static assignment. The analyst should examine the details with the convergence criteria and set an acceptable convergence criterion for their analysis. Two categories of convergence criteria have been used: link-based and trip-based. A link–based criteria are based on the condition that that the link flows reach stable state and do not fluctuate with additional assignment iterations while a trip-based criterion is based on the stability of the flows assigned to the paths (and/or the travel times of the paths) between each O-D pair. Path-based methods, if available in the utilized DTA tool, is preferred.

The assessment of convergence is important to ensure the quality of traffic assignment results. The convergence of user equilibrium assignment is necessary to ensure the integrity of the solution. Such integrity is required to ensure that the model can be used to properly assess alternative designs and operational strategies.

3.8.5 Demand Estimation

Dynamic traffic assignment requires time-dependent O-D demand matrices as demand inputs. One source of such matrices are the FSUTMS demand forecasting models. However, it has been found that in many cases, assigning the matrices obtained from the demand forecasting models to the network does not produce segment and turn movement volumes of sufficient accuracy. The traffic assignment tool vendors have developed O-D matrix estimation (ODME) modules to estimate the O-Ds based on initial seed matrices usually obtained from demand forecasting models combined with segment and/or turn movement counts. The specification of turning movement counts rather than segment counts improve the accuracy of the estimation. Some tools allow using other measures in the estimation such as production/attraction data, travel times, densities, and queues. In recent years, data from private sector vendors and/or Bluetooth readers have also been used in the O-D estimation.

In general, the problem of O-D estimation is underspecified, meaning that different O-D demand matrices produce the same set of link volumes if assigned to the network. Thus, the user should be careful when running these procedures to estimate demand. The user should carefully examine the resulting matrices and counts compared to the count measurements, partial O-D demand measurements, and demand matrix estimation. There is a need to limit the deviation of the estimated O-D matrix from the seed O-D matrix if there is a high confidence in the initial matrix. Certain features of the matrix may be necessary to keep. Some utilities allow the user to put constraints on the optimization such as fixing specific O-D flows, specifying or fixing production/attraction counts, or even limiting the percentage of vehicles using a specific O-D path. For instance, the user may want to preserve the number of production and attraction trips for each zone.

Some tools allow the use can also put weights on specific link counts, specific O-D pair demands, and the relative importance of O-D matrices versus counts in the ODME process. The user should examine the impacts of these parameters on the result quality using measurements, observations, local knowledge, and engineering judgment in the process

3.8.6 Zone and Connector Disaggregation

Regional demand model usually consists of traffic analysis zones (TAZs) that are usually too large for mesoscopic or microscopic simulation. Simulation modeling works better with more refined zone representation to allow appropriate access to the network. The analyst may want to utilize the micro zone representation available in some FSUTMS models. There are also a number of approaches that can help to disaggregate trips from the TAZs to smaller zones. The simplest approach is to distribute trips to the smaller zones based on the ratio of the subarea zone area to the larger regional zone. This approach does not take into account the locations of developments within the zone. Sloboden et al. recommended distributing the trips based on the actual land uses by applying trip rates from the Institute of Transportation Engineers (ITE) Trip Generation Manual or by applying trip rates from the regional model (Sloboden et al., 2012). The analysis team should also examine the locations of zone connectors to the network, to ensure that they provide reasonable and realistic access.

3.9 MULTIRESOLUTION MODELING

Multiresolution modeling (MRM) references the integration of different resolutions of simulations such as the demand forecasting, macroscopic, mesoscopic, and microscopic models to achieve the modeling project objectives. Depending on the project under consideration, each type of tool can play a role in the modeling process utilized in the project. Combinations of advanced modeling tools and methods are particularly needed for analyzing recurrent and non-recurrent congested conditions and associated mitigation strategies that impact the strategic behaviors of travelers. MRM is also needed for modeling advanced strategy applications such as managed lanes (ML), dynamic pricing, active traffic management, smart work zones, incident management, freight corridors, integrated corridor management, automated/connected vehicle implementations, bus rapid transit (BRT), and other intelligent transportation systems (ITS) and transportation system management and operations (TSM&O) strategies. Depending on the level of the analyses and the specific problem under consideration, a number of tools have been used to assess these strategies, including tools that can be classified as sketch planning, dynamic traffic assignment, macroscopic simulation models, mesoscopic simulation models, microscopic simulation models, and combinations of these tools. Additional details are presented later in Chapter 5 of this report when discussing the findings from Task 4 of the project.

3.10 MODELING OF CONNECTED AND AUTOMATED VEHICLES

The guidance of modeling of connected and automated vehicles presented in this section was developed as a joint effort between this project and a project entitled “Utilization of Connectivity and Automation in Support of Transportation Agencies’ Decision Making” funded by the Southeastern Transportation Research, Innovation, Development and Education Center (STRIDE), a Regional University Transportation Center (UTC) sponsored by a grant from the U.S. Department of Transportation's University Transportation Centers Program. Additional information about CAV modeling will be included in the final report of that project (Hadi et al. forthcoming). Some of the text in this section will also appear in that final report.

3.10.1 Vehicle Connectivity, Automation, and Collaboration

In the coming years, it is expected that the traffic stream will consist of a mixture of vehicles with different levels of automation and connectivity including autonomous vehicles, (AV), connected vehicles (CV), connected automated vehicles, and manually driven vehicles.

Connected vehicle (CV) technologies will provide significant improvements in system performance. The United States Department of Transportation (USDOT) identified a large number of vehicle-to-infrastructure (V2I), vehicle-to-vehicle (V2V), and vehicle-to-everything (V2X) applications classified in three categories: mobility, safety, and environmental applications. The dynamic mobility applications (DMA) program of the USDOT identified high-priority mobility applications (USDOT, 2022). Table 3-4 summarizes applications that use V2I communications. There are also a large number of V2I safety applications. These includes signalized intersection applications such as red-light violation warning and pedestrian on crosswalk, unsignalized intersection applications such as gap acceptance assist, and segment-level applications such as reduced speed warning and back of queue warning.

Table 3-4 USDOT program DMA bundles and applications

Bundle	Applications
Freight Advanced Traveler Information System (FRATIS)	Freight Specific Dynamic Travel Planning and Performance, Drayage Optimization (DR-OPT)
Integrated Dynamic Transit Operation (IDTO)	Connection Protection (T-Connect), Dynamic Transit Operations (T-DISP), Dynamic Ridesharing (D-RIDE)
Response, Emergency Staging and Commutations, Uniform Management, and Evacuation (R.E.S.C.U.M.E.)	Incident Scene Pre-Arrival Staging Guidance for Emergency Responders (RESP-STG), Incident Scene Work Zone Alerts for Drivers and Workers (INC-ZONE), Emergency Communications and Evacuation (EVAC)
Multimodal Intelligent Traffic Signal System (MMITSS)	Intelligent Traffic Signal System (I-SIG), Transit and Freight Signal Priority (TSP and FSP), Mobile Accessible Pedestrian Signal System (PED-SIG), Emergency Vehicle Preemption (PREEMPT)
Intelligent Network Flow Optimization (INFLO)	Dynamic Speed Harmonization (SPD-HARM), Queue Warning (Q-WARN), Cooperative Adaptive Cruise Control (CACC)
Enable Advanced Traveler Information Systems (Enable ATIS)	EnableATIS (Advanced Traveler Information System 2.0)

With regard to vehicle automation, there are six different levels of automation according to the Society of Automotive Engineers (SAE) J3016 standards – Taxonomy and Definitions for Terms Related to for On-Road Motor Vehicles (SAE, 2021a). The six levels are:

- No automation (Level 0): Driver manually executes all driving functions such as brake, steering, car following etc.

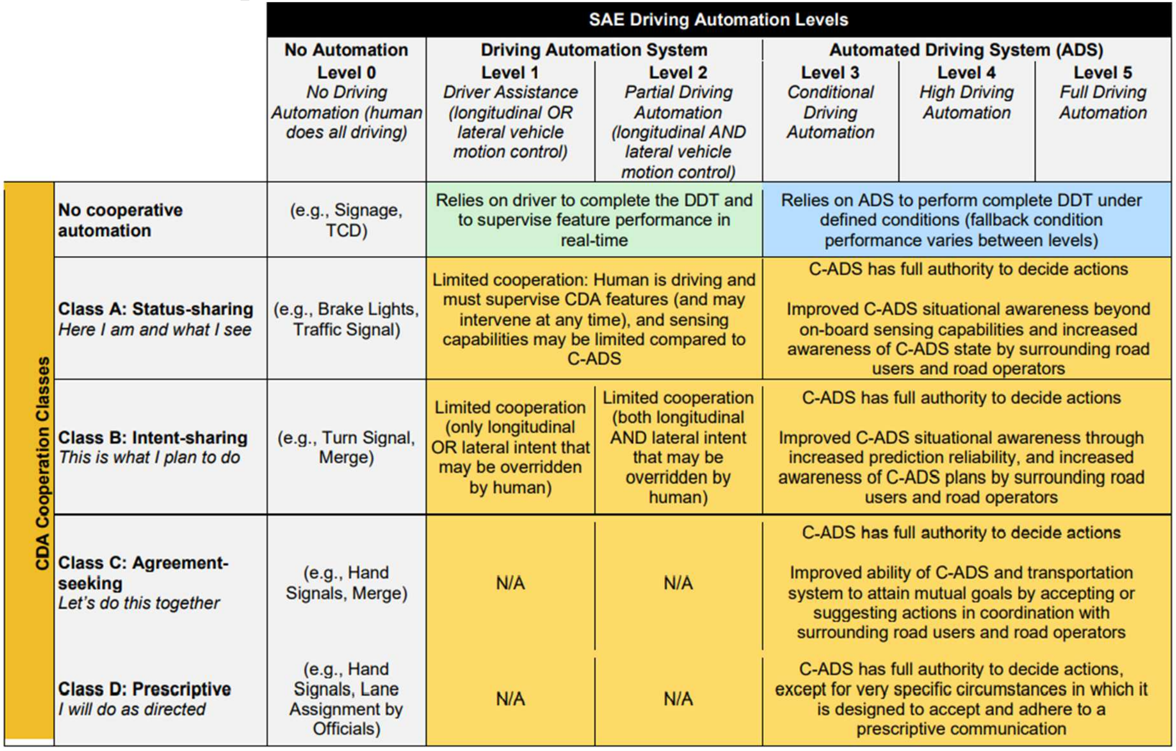
- Driver Assistance – Function-specific automation (Level 1): ODD-specific execution by a driving automation system of either the lateral or the longitudinal vehicle motion control subtask (but not both simultaneously) with the expectation that the driver performs the remainder of the driving tasks.

- Partial Driving Automation (Level 2): The sustained and ODD-specific execution by a driving automation system of both the lateral and longitudinal vehicle motion control but the driver has to constantly monitor the roadway while driving and be ready to take over these controls in a short time.
- Conditional driving automation (Level 3): The sustained and ODD specific performance by system of all driving tasks with the expectation that the system can issue requests to intervene.
- High Driving Automation (Level 4): The sustained and ODD-specific performance by an ADS of the entire DDT without any expectation that a user will respond to a request to intervene.
- Full driving automation (Level 5): The sustained and unconditional (i.e., not ODD specific) performance by the system of all driving tasks without any expectation that a user will respond to a request to intervene.

SAE also defines classes of cooperative driving automation in SAE J3216 standards, which also identifies the relationships between the classes and levels of automation previously defined in SAE J3016 (SAE, 2021a, 2021b). SAE J3216 classifies the CDA into four classes according to the capability of sharing state information (e.g., vehicle position, signal phasing and timing), sharing of intent (e.g., planned vehicle trajectory, changes to signal timing), and ability to seek agreement on a plan such as coordinated merge, lane change, or platooning. The nature of the cooperation differs based on the level of driving automation. For driver support features (SAE driving automation Levels 1 and 2), only limited cooperation may be achieved since these levels rely on the human driver to do at least some of these functions. For Levels 3 through 5 automation, more substantial cooperation may be achieved.

Table 3-5 describes the relationship between cooperation and automation as presented in SAE J3216 standards.

Table 3-5 Relationship between classes of CDA cooperation and levels of automation, as presented in SAE J3216 Standards (SAE, 2021b)



		SAE Driving Automation Levels					
		No Automation	**Driving Automation System**		**Automated Driving System (ADS)**		
		Level 0 *No Driving Automation (human does all driving)*	**Level 1** *Driver Assistance (longitudinal OR lateral vehicle motion control)*	**Level 2** *Partial Driving Automation (longitudinal AND lateral vehicle motion control)*	**Level 3** *Conditional Driving Automation*	**Level 4** *High Driving Automation*	**Level 5** *Full Driving Automation*
CDA Cooperation Classes	**No cooperative automation**	(e.g., Signage, TCD)	Relies on driver to complete the DDT and to supervise feature performance in real-time		Relies on ADS to perform complete DDT under defined conditions (fallback condition performance varies between levels)		
	Class A: Status-sharing *Here I am and what I see*	(e.g., Brake Lights, Traffic Signal)	Limited cooperation: Human is driving and must supervise CDA features (and may intervene at any time), and sensing capabilities may be limited compared to C-ADS		C-ADS has full authority to decide actions Improved C-ADS situational awareness beyond on-board sensing capabilities and increased awareness of C-ADS state by surrounding road users and road operators		
	Class B: Intent-sharing *This is what I plan to do*	(e.g., Turn Signal, Merge)	Limited cooperation (only longitudinal OR lateral intent that may be overridden by human)	Limited cooperation (both longitudinal AND lateral intent that may be overridden by human)	C-ADS has full authority to decide actions Improved C-ADS situational awareness through increased prediction reliability, and increased awareness of C-ADS plans by surrounding road users and road operators		
	Class C: Agreement-seeking *Let's do this together*	(e.g., Hand Signals, Merge)	N/A	N/A	C-ADS has full authority to decide actions Improved ability of C-ADS and transportation system to attain mutual goals by accepting or suggesting actions in coordination with surrounding road users and road operators		
	Class D: Prescriptive *I will do as directed*	(e.g., Hand Signals, Lane Assignment by Officials)	N/A	N/A	C-ADS has full authority to decide actions, except for very specific circumstances in which it is designed to accept and adhere to a prescriptive communication		

3.10.2 CAV Modeling Framework

Although this document mainly focuses on microscopic simulation of CAV, the analyst needs to understand that in many projects, microscopic simulation is a component of a larger AMS effort that involve other analysis types including demand forecasting tools, mesoscopic simulation based dynamic traffic assignment, other behavioral modeling tools and algorithms, and highway capacity analysis tools. In addition, the analyst should consider the need to model CAV as part of a more comprehensive assessment of emerging technologies and strategies including automated, connected, electric, and shared (ACES) vehicles and transportation system management and operations (TSM&O).

The FHWA developed a comprehensive CAV AMS framework (Mahmassani et al., 2018). Although the framework was produced to inform CAV AMS model development effort, it can be used a basis for a project level AMS framework by the analysis team. The framework includes four main dimensions of CAV modeling: Supply Changes, Demand Changes, Performance Changes, and Network Integration. These four dimensions of CAV modeling as listed below can be used for the setting of the project level CAV framework. It should be noted that depending on the AMS objectives and scopes, all or a subset of the four dimensions need to be included in the project modeling framework.

- ***Supply Changes:*** The increase in the market penetration of the CAVs will be accompanied with changes to the physical and digital infrastructure including those that enable V2I connectivity, in addition to enabling new mobility options such as mobility as a service, shared fleet utilization, last mile automation, and automated trucks. The assumptions about supply changes and the associated performance are important parts of the CAV modeling process.

- ***Demand Changes:*** CAV is expected to have significant impacts on activity and travel choices. It is expected that there will be major impacts due to the changes in the value-of-time due to multitasking and changes in various performance metrics of traveling. AT high levels of automation (Levels 4 and above according to SAE J3106 standards), the reduction in the stress of travel and the ability to perform other tasks while in the vehicle are expected to reduce the value of travel time, potentially increasing the number of trips and vehicle miles travelled. Shared mobility enabled by CAV will also have significant impacts on demand generation and associated activities and the decision to own a vehicle. In addition to trip generation, it is expected that CAV will impact other travel activities such as mode choice, route choice, and departure time, among others. The estimation of the demand changes requires enhanced demand forecasting models that can effectively determine the impacts of CAV on trip generation, distribution, mode choice, trip time, route choice, and even land use. This demand forecasting component is beyond the scope of this document.

- ***Operational Performance:*** CAVs will have significant impacts on capacity and stability of the traffic stream. Thus, there will be significant improvements in travel time and travel time reliability. CAVs will also have significant impacts on other measures such as safety, environmental impacts, equity, and resilience measures, among others. The assessment of the operational performance and impacts of CAV using microscopic simulation is the major focus of this project. CAV AMS should be able to capture the interactions between the vehicles, infrastructure and others like pedestrians and bicycles considering heterogeneous mix of traffic including manual drivers, different levels of automated vehicles with and without connectivity, and vehicles with different classes of collaboration. These vehicles will have different reaction times, driving errors, acceleration/deceleration, car following headways, gap acceptance, lane changing, speed setting, merging, and weaving behaviors. It is recognized that these behaviors are expected to vary depending on the equipped sensors, wireless communications, and the control algorithms installed by different car manufacturers. However, it is also recognized that an abstraction of the resulting behaviors is acceptable for many CV AMS applications in the absence of more detailed information about the performance of the implementations of these manufacturers.

- ***Network Integration:*** The CAV modeling may include multiple tools, tool extensions, algorithms, and preprocessing and post processing tools. There is a need to integrate the tools capture the ACES interactions at the network level.

3.10.3 Identification of the Technical Approach

As stated earlier in this document, there is a wide variation of the types of connected, automated, and cooperative applications. Only a subset (that can be a small subset) of these types and applications will need to be modeled in a given project. The modeling of CAV will increase the complexity and uncertainty associated with the AMS tasks and thus the required resources. The

CV AMS effort should focus on the needs of the project and model only the subset of CAVs and applications that need to be modeled. Thus, the analyst needs to clearly understand the project goal objectives and work with other stakeholders to potentially clarify or even revise the goal and objectives, if need to.

The study objectives reflect the system needs and will provide the basis for selecting the evaluation alternatives. The analyst should work with the stakeholders of the project to identify the evaluated alternatives, formulate the hypotheses to be addressed by the analysis in relationship to project goal and objectives, the performance measures, and the modeling framework.

The additional complexities associated with CAV modeling should be considered in the early stages of the project to determine the required capability and resources and to confirm that these requirements can be met. The technical approach should be carefully identified in as much level of details as possible. It is realized that no single existing AMS tool has the capabilities required to analyze all aspects and applications of CAV. A combination of tools may be needed. In addition, many of the required modeling components for CAV do not exist in the existing modeling tools. Thus, additional programming to extend the modeling capabilities of the existing tools is often needed using for example the Application Programming Interface (API) of commercially available tools.

A recent FHWA project (Halkias & Abbas, 2020) identified the steps required to select the analysis approach as follows: define the scope, the questions to be answered by modeling, a list of needs and requirements to answer the questions, and the ranking and prioritization of the list. Based on the above, the analyst will identify the approach considering the available tool(s) capabilities and determining the level of customization needed. The project team should then define and evaluate the tasks, determine whether the analysis can be done given the resources, and weigh the number of questions that can be answered considering the resources. This process will also identify the data needs and availability (further discussion of this is presented in a separate subsection). The above mentioned FHWA study recommended using what is referred to as the Pillar diagram that is intended to facilitate the brainstorming process recommended to select the modeling approach. The Pillar Diagram includes three pillars (components) that addresses four possible levels of analysis details within each pillar: (1) activity-based modeling (ABM) and Origin-Destination analysis, (2) microscopic analysis, and (3) macroscopic analysis, as shown in Figure 3-5. For each of the components, there are four types of possible types of analysis that can be identified:

- Standard features in existing AMS tools
- Capabilities obtained through scripting or Application Programming Interface (API).
- Capabilities that can only be obtained through tools developed outside the available AMS tools.
- Capabilities that can only be obtained through development of new tools or frameworks.

It is recommended that the CAV analyst review the deliverables from the above mentioned FHWA study and utilize the methodology proposed in that project in selecting the analysis approach. Once the approach is selected, then the specific tool(s) to be used in the analysis will have to be selected. Further discussion of the selection of the tool(s) is presented later in this section.

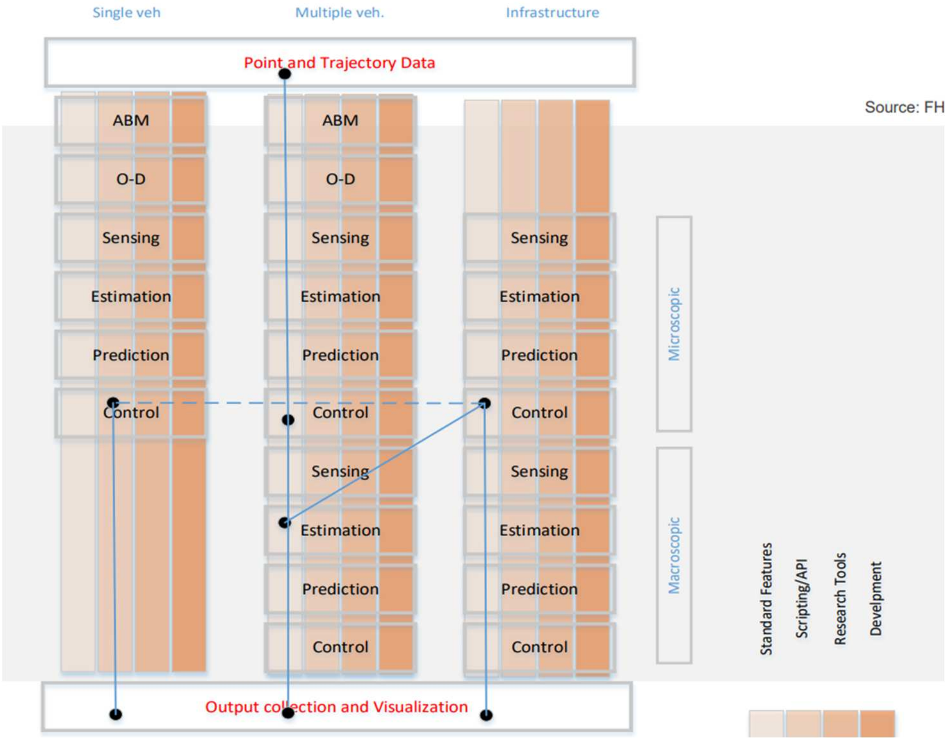


Figure 3-5 An example of the pillar diagram recommended in the FHWA study (Halkias & Abbas, 2020)

3.10.4 Uncertainties Associated with CAVs

AMS can be conducted to assess the impacts of CAV in various time periods in the future ranging from short-term to long-term. When simulating CAV, it is important to estimate the CAV adoption since the market penetrations of different levels and classes of CAVs in the traffic stream will determine the system performance. Studies have been conducted to provide information regarding the increase in the market penetrations of the CAV. However, there is still significant uncertainties regarding this increase. There are many issues that will impact the rates of the adoption of various types of CAVs, depending on the specific connectivity and automation capabilities. These include the cost of the technology, whether the technology is used in private or shared vehicles, the progress in determining the actual safety of technology, the provision of the required infrastructure support, policy and legal issues, and technology progress. Todd Litman predicted a range of potential market penetrations for various years in the future, as shown in Figure 3-6 (Litman, 2020).

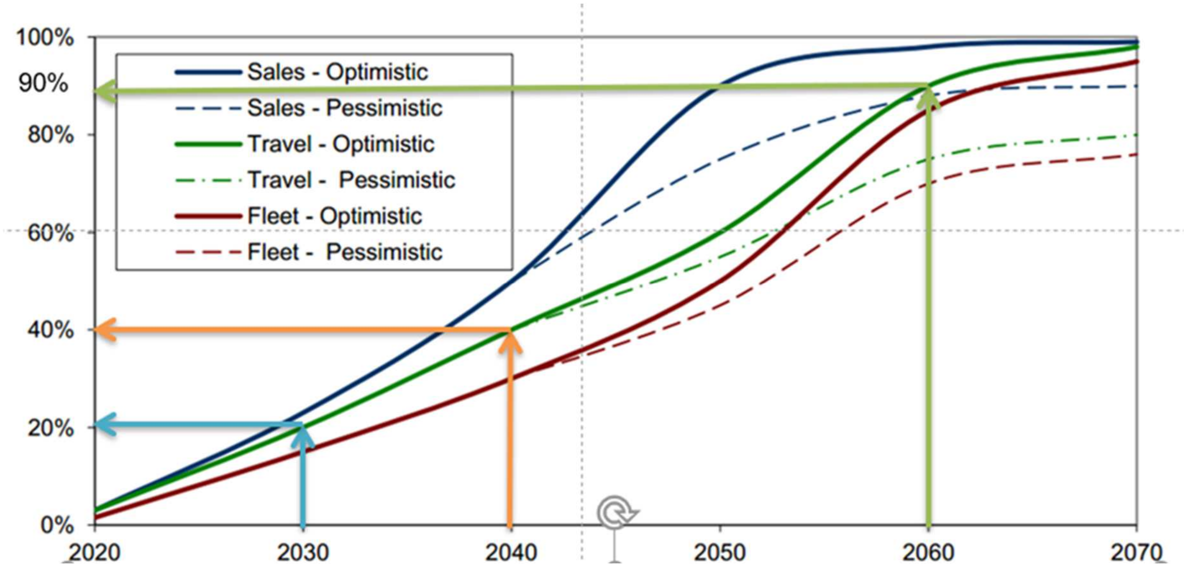


Figure 3-6 Prediction of CAV and AV introduction timeline (Litman, 2020)

The uncertainty described above will have to be considered in the CAV AMS. Previous studies have described Scenario Planning as the basic method for planning under deep uncertainty and as a step incorporated in performance-based planning at various stages of the process (Twaddell et al., 2016). It is recommended that such an approach should be used in CAV AMS since the timeline for adoption of CAV technology is debatable. In setting the parameters for scenario-based planning, the analysts should review the recent studies on the subject of CAV adoption and assess the confidence levels in these studies. CAV adoption ranges similar to those estimated by Todd Littman can be used in the scenario analysis (Litman, 2020). The project should also reach consent among stakeholders about the potential timing of deployment to support the process of scenario development. There is also a need for understanding how to communicate the results under uncertainty is fundamental to a conceptual framework for planning and modeling CAVs.

3.10.5 Performance Measure Identification

An important aspect of the hypothesis formulation is to identify performance measures that are relevant to the project goal and objectives and expected impacts of CAV on different measures. Thus, in addition to realizing the project goal and objectives, it is important that the analysts understand the wide range of CAV levels and classes and associated applications and use cases. Such impacts are dependent on the market penetration of the technologies as discussed further later in this chapter.

CAV applications are expected to improve mobility measures by increasing throughput, probability of breakdown, and stability. The latest version of the Highway Capacity Manual (HCM) includes CAV specific sections that recommend capacity modification factors for freeway segments considering different market penetrations of vehicles equipped with CACC operations and dynamic merge operations. In addition, it provides capacity modification factors for protected through, protected left, and permissive left turn movements at signalized intersections. AMS can be used to quantify CAV impact on traffic flow breakdown measures such as the occurrence, severity, duration, and intensity of the bottleneck and formed shockwaves. The above improvements are expected to improve other key performance indicators such as travel time, travel time reliability, delay, number of stops, percentage time in congestion, travel time reliability indices, and so on.

It is recognized that safety is an important factor in evaluating the impacts of CAV, considering that these technologies will be able to reduce or eliminate crashes that are due to human error, depending on the levels of automation. These measures are the most difficult to estimate using simulation, considering that in microscopic simulation usually assumes that the drivers are safe drivers, and they conduct versus activities such as car following, lane changing, merging, and gap acceptance in a safe manner. However, in many cases, the analysts can assess the impacts of CAV and associated applications using surrogate measures based on the trajectories produced by microscopic simulation models. Further discussion of safety assessment is presented when discussing the Alternative Analysis step in this document.

Sustainability is also an important consideration when setting the measures to assess the environmental impacts of CAV, considering the smoother operations associated with CAV. The estimation of the changes in pollutant emission can be estimated by providing inputs to models like the MOVES model developed by the Environmental Protection Agency (EPA), based on processing the trajectories of the simulated vehicles are estimated. It should be mentioned that the sustainability metrics will be also significantly impacted by electric vehicles that are expected to increase in market penetrations in the next few years.

3.10.6 Data Requirements and Availability

Data requirements, availability, quality, consistency, and filling the data gaps are critical considerations in the planning and when scoping the project and selecting the modeling approach for the project (Wunderlich et al., 2017). Analysts need to examine the data requirements and availability at the scoping stage to reduce the risks associated with CAV modeling. This is consistent with the data-driven analytic project scoping process recommended in "Scoping and Conducting Data-Driven 21st Century Transportation System Analyses" (Wunderlich et al., 2017). The modeling for CAV requires trajectory level data/high resolution data for manual driving vehicles as well as CAVs. In this regard, the analyst needs to examine the default microscopic traffic parameters in the utilized tools and models and how these parameters were derived. In some cases, the parameters have been selected based on real-world data collected from field deployment or test track. Abbas et al. refers to this type of data as encapsulated data (Halkias & Abbas, 2020). For example, the Vissim microscopic simulation tool set the car following parameters of CAVs based on the Co-Exist project in Europe. The analysts need to examine any encapsulated data in the model and determine if it is adequate for the analysis. When the encapsulated data is not available or not adequate, then the analyst will need to borrow the traffic flow parameters from previous studies, utilize data collected and archived by others, and/or collect data based on a data collection plan considering the limited real-world deployment of CAVs. Further discussion of data collection is presented later in this chapter.

3.11 SETTING CALIBRATION TARGETS

3.11.1 Introduction

Calibration is the process of modifying simulation model parameters to enhance a model's capability in emulating time-dynamic system performance observed under particular travel situations (Wunderlich et al., 2019). Several techniques and guidelines are available to calibrate traffic simulation models. Analysts usually use time-variant macroscopic measures in the calibration process, such as volume, capacity, queue discharge flow, speed, and travel times (Dowling et al., 2004b; Hourdakis et al., 2003). The Traffic Analysis Toolbox Volume III, released by the Federal Highway Administration (FHWA) in 2019, provides a detailed traffic simulation development and calibration methodology, which is a revision of the methodology presented in the 2004 version of this document (Dowling et al. 2004a; Wunderlich et al., 2019). The 2019 methodology provides a detailed discussion of the use of data for calibration, identifies performance measures and scenarios for modeling based on clustering, selects a representative day for each modeled scenario, and sets calibration targets for each scenario. The methodology in the 2019 version replaced the concept of using fixed calibration targets in the 2004 version with the concept of targets that vary by segment, time period, and simulated operational scenario depending on the day-to-day variations in the calibrated measure values (Dowling, Skabardonis, & Alexiadis, 2004; Wunderlich et al., 2019). The methodology provides four criteria for calibration and methods to estimate the targets associated with each criterion. These four criteria are based on the standard deviation of the observed data and the deviation between the observed data and simulated data, as described later.

In recent years, several state departments of transportation (DOTs) have developed analysis, modeling, and simulation (AMS) guidelines with a strong emphasis on model calibration. These include, for example, the Florida Department of Transportation (FDOT) (FDOT Systems Planning Office, 2014), Iowa Department of Transportation (IDOT) (Iowa DOT, 2017), Virginia Department of Transportation (VDOT) (VDOT, 2020; VDOT Traffic Engineering Division, 2020), Washington State Department of Transportation (WSDOT) (Schilperoort et al., 2014), Oregon Department of Transportation (ODOT) (Mai et al., 2011), and Wisconsin Department of Transportation (WisDOT) (WisDOT, 2019). The measures of effectiveness (MOEs) used to calibrate the microsimulation model usually include capacity, traffic volume, travel time, speed, intersection delay, and queue length, with volume and travel time being the most frequently used MOEs in the calibration. Unlike the updated FHWA methodology, the guidance documents of the state DOTs provide fixed thresholds for each MOE used in calibrating the simulation models and many of them are based on the 2004 FHWA guidance mentioned above.

Only a few studies exist that explain the rationale behind and the justification for selecting calibration targets for the measures in the state guidelines. As transportation agencies consider the possibility of adopting the 2019 FHWA calibration methodology, questions are being raised by the simulation community on how differently the values of the varying targets are calculated using the FHWA methodology compared to the existing fixed targets that have been used in the industry for a long time. The purpose of this study is to compare the results from the use of varying calibration targets, as proposed in the methodology in the 2019 guidance, with the fixed targets in the state DOT guidance. The comparison is made utilizing data from urban freeway facility segments with different day-to-day variations in the values of the MOEs.

3.11.2 Literature Review

Studies found that the absence of proper guidelines for model calibration will lead to incorrect model results (Hourdakis et al., 2003; Milam & Choa, 2001). Based on interviews with professionals, published articles, and completed simulation projects, Milam and Choa, in an early study, recommended a set of guidelines to calibrate and validate traffic simulation models (Milam & Choa, 2001). Chu et al. provided a multistage and systematic calibration process by considering microscopic driving behavior and route choice model parameters (Chu et al., 2003). Dowling et al. suggested a three-step framework for calibrating microsimulation models consisting of calibrating bottleneck capacity, route choice, and system performance (Dowling, Skabardonis, Halkias, et al., 2004). The authors highlighted the calibration targets utilized by WisDOT in a 2002 project, which was based on the guidelines of the Department for Transport, London, United Kingdom (Department for Transport London, 1996; WisDOT, 2019). It appears that the United Kingdom guidance is the source of information used in the 2004 version of the FHWA guidelines and later in many state agency guidance.

Gomes et al. proposed qualitative approaches to calibrate a microsimulation model of a freeway based on detailed data collected from traffic sensors (Gomes et al., 2004). Menneni et al. calibrated a microsimulation model by matching speed-flow relationship graphs derived from field measurements and simulation outputs (Menneni et al., 2008). Otković et al. developed a neural network approach to calibrate microsimulation models based on travel time and queuing measures (Otković et al., 2013). Oh et al. developed a weighted simultaneous perturbation stochastic approximation (W-DSPSA) method to effectively calibrate the demands in a microscopic network simulation model (Oh et al., 2019). Sha et al. proposed a Bayesian optimization framework for the high-dimensional calibration problem in transportation simulation models (Sha et al., 2020). Tariq et al. utilized high-resolution signal controller data in combination with a bi-level unsupervised clustering technique and multi-objective optimization to calibrate and validate microsimulation simulation models (Tariq et al., 2021).

Simulation model calibration in practice has been a manual process (Hollander & Liu, 2008). Automated optimization algorithms have been proposed to calibrate the simulation models. Studies showed that heuristic optimization approaches such as genetic algorithms (Kim et al., 2004; Zhang et al., 2006), memetic algorithms (Paz et al., 2015), simplex-based calibration (Kim & Rilett, 2003), simultaneous perturbation stochastic approximation (SPSA) (Lee & Ozbay, 2009), simulated annealing (Hoyer & Fellendorf, 1997), complex algorithms (Toledo et al., 2004), Swarm algorithm, and even trial-and-error enumeration (Gomes et al., 2004) can improve the simulation's calibration performance (Karimi et al., 2019). However, the automated calibration approaches are complex and require high computational effort. Thus, automated calibration of simulation models has not been widely used in practice.

3.11.3 Study Tasks

A flowchart of the research approach in this study is shown in Figure 3-7. This study first compared the calibration target setting as recommended in the guidelines of the Florida, Iowa, Virginia, Washington State, Oregon, and Wisconsin DOTs. Next, the study examined the method to calculate varying targets by segment, time interval, and modeled scenario as recommended in the 2019 version of the "Traffic Analysis Toolbox Volume III" developed by the FHWA (Dowling, Skabardonis, & Alexiadis, 2004). The study then compared the use of these varying thresholds to the traditionally used fixed thresholds utilizing a freeway case study.

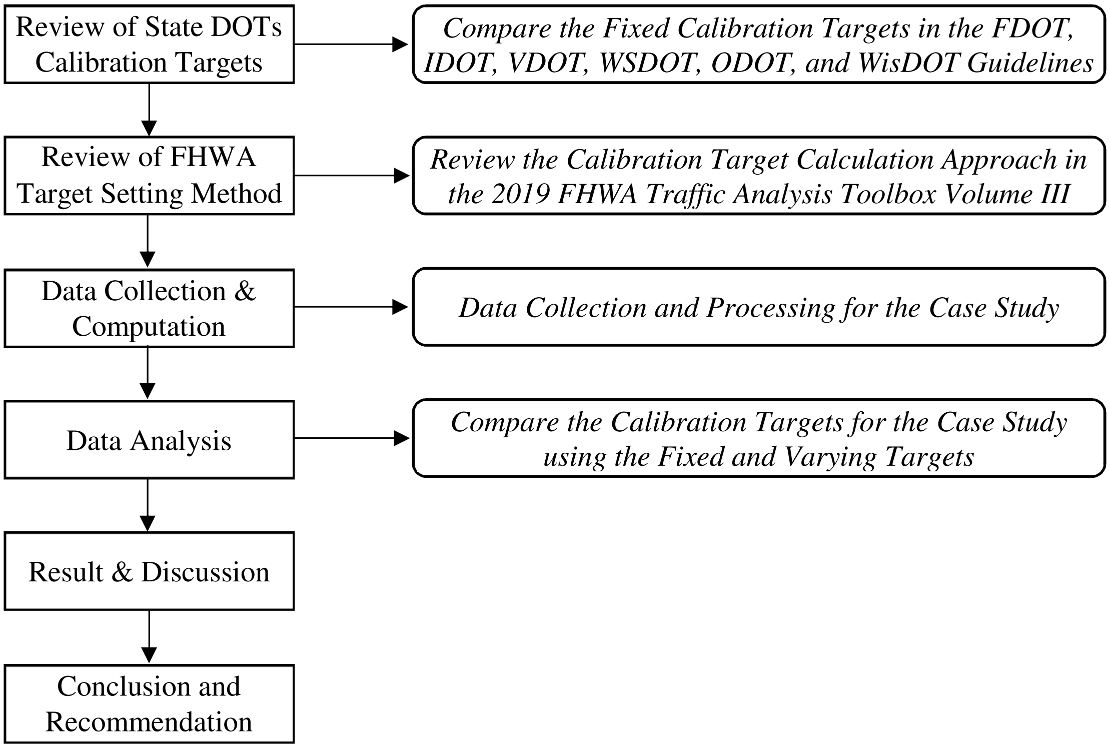


Figure 3-7 Research approach of this study

3.11.4 Calibration Targets in the State DOT Guidelines

Table 3-6 summarizes the calibration targets for microsimulation models used by FDOT (FDOT Systems Planning Office, 2014), IDOT(Iowa DOT, 2017), VDOT(VDOT Traffic Engineering Division, 2020), WSDOT(Schilperoort et al., 2014), ODOT(Mai et al., 2011), and WisDOT (WisDOT, 2019). Table 3-6 indicates that volume, travel time (TT), and speed are the most used measures in the calibration of microsimulation models. Some states also use intersection delay, queue length, and lane utilization in the calibration. Table 3-6 shows that different states use several types of the goodness of fit criteria, including value difference, percentage difference, Root Normalized Squared Error (RNSE), Root Mean Squared Percent Error (RMSPE), and the Geoffrey E. Havers Tolerance (GEH) formula. Only the FDOT and IDOT have calibration targets for capacity at the bottlenecks, requiring the simulated capacity to be within 10% of the field-observed capacity.

Table 3-6 Comparison of the calibration targets in the guidance of state agencies

MOEs	Calibration Targets	FDOT	IDOT	VDOT	WSDOT	ODOT	WisDOT
Traffic Volume	Simulation link Volume to measured field volume for more than 85% of the links of the model	± 100 vph for < 700 vph	± 100 vph for < 700 vph	*±20% for <100 vph*		± 400 vph for > 2700 vph	RMSPE < 5% for > 100 vph (Tier 1)
		± 15% for 700-2700 vph	± 15% for 700-2700 vph	*±15% for 100-1000 vph*			RNSE < 3% for > 100 vph (Tier 2)
		± 400 vph for > 2700 vph	± 400 vph for > 2700 vph	*±10% for 1000-5000 vph*			RNSE < 3% for > 75% of all turns
				± 500 vph for ≥5000 vph			
	GEH for 85% or more simulated links' volume	5 or less	N/A	N/A	< 5 (local roadway)	<5 (Freeway only)	
	Sum of link volumes within calibration area	± 5%	N/A	N/A	± 5%	± 5%	
	GEH for the sum of all link volumes within the calibration area	5 or lower	N/A	N/A	< 3 (all state roadway)		
	GEH at all entry & exit locations and entry & exit ramps within the calibration area	N/A	N/A	N/A	< 3	<5	
Travel Time, TT (includes Transit)	Simulated TT versus observed TT	See the cells below	See the cells below	within 30% of the observed values for arterial streets and 20% for freeways		See the cells below	RMSPE shall be < 10%, and simulated TT shall be within ± 15% for more than 85% of routes with a length greater than 1.5 miles.
	Simulated TT to observed for more than 85% of the network links; Routes with ≤ 7 min TT	± 1 min	± 1 min			± 1 min	
	Simulated TT to observed for more than 85% of the network links Routes with > 7 min TT	±15%	± 15%			± 15%	
Spot Speed (mph)	Average link speed model to field measured for at least 85% of links	±10 mph	±10 mph			± 10 mph	±20%
	Spot speed in the model to field measurement				Uninterrupted flow: ± 3 mph Interrupted flow: ± 10%	± 10%	RMSPE < 10%

MOEs	Calibration Targets	FDOT	IDOT	VDOT	WSDOT	ODOT	WisDOT
Queue Length	Simulation queue length to field	± 20%	±20%	Visually accepted	Qualitative analysis required	Qualitative analysis required	± 150 ft for 300-750 ft queue, ±20% for > 700 ft queue
Lane Use	Lane utilization, model vs. field	Visual Check			Should use lane-by-lane volume and follow volume criteria	GEH ≤ 5	RNSE 3% for >85% of critical lanes

Table 3-6 shows that the FDOT and IDOT have the same criteria that specify the simulated link volumes for more than 85% of links to be within 100 vehicles per hour (vph) of field measurements for volumes less than 700 vph, within 15% of field measure for volumes between 700 vph and 2700 vph, and within 400 vph of field measure for volumes greater than 2700 vph. The ODOT has the same criterion as the FDOT and IDOT for link volumes higher than 2700 vph) but does not specify the criteria for other link volumes. However, both the FDOT and ODOT also use the GEH as a measure in the calibration process. The VDOT uses different targets for volume calibration, and the WisDOT utilizes the RMSPE and RNSE goodness of fit criteria instead of the percent and/or value difference used by other states.

For travel time, the FDOT, IDOT, and ODOT have the same thresholds for calibration, and the rest of the states have different thresholds. These three state DOTs specify that the simulated travel times for more than 85% of the network links should be within one minute of the field measurements for links with TT of less than or equal to 7 minutes (min) and ± 15% for links with TT more than 7 min. It should be noted that the FDOT, IDOT, and ODOT utilize values similar to the values presented as example targets in the 2004 version of the FHWA Traffic Analysis Toolbox Volume III based on guidance used by WisDOT in 2002 (Dowling, Skabardonis, & Alexiadis, 2004; WisDOT, 2019). As stated earlier, that guidance was based on the guidelines of the Department for Transport, London, UK (Department for Transport London, 1996; WisDOT, 2019). The VDOT requires the simulated values to be within 30% of the observed values for arterial streets and within 20% for freeways. The WSDOT uses equations to set the calibration target for TT as a function of real-world TT, segment length, and free-flow speed. The WisDOT specifies a target RMSPE of less than 10% for the simulated TT and that the simulated TT shall be within ± 15% for more than 85% of routes with a length greater than 1.5 miles.

3.11.5 Varying Calibration Target Method

As stated earlier, the FHWA has introduced a method for identifying calibration targets that vary by segment, time interval, and operational scenario (Wunderlich et al., 2019). This method selects a representative day for each modeled operational scenario. The operational scenarios are identified using clustering analysis based on traffic operation parameters such as volumes and travel times, incidents, weather events, and work zones. The guidance then specifies calibration targets in that all model variants (performance measures) should meet the following four criteria:

Criterion I: Control for Time-Variant Outliers – About 95% of simulated outputs must fall within a wide statistical range or two-sigma band range, i.e., $c_r(t) \pm 1.96 \times \sigma(t)$ around the representative day values.

Criterion II: Control for Time-Variant "Inliers" – Two-thirds of simulated results must fall within a narrower range or one-sigma band, i.e., $cr(t) \pm \sigma(t)$ around the representative day values.

Criterion III: Bounded Dynamic Absolute Error (BDAE) – This condition must meet the following:

$$\frac{\sum_t |c_r(t)\text{-}\tilde{c}_i(t)|}{N_T} \le \text{BDAE Threshold}$$

Criterion IV: Bounded Dynamic Systematic Error – This condition must meet the following:

$$\left|\frac{\sum_t c_r(t)\ \text{-}\tilde{c}_i(t)}{N_T}\right| \le \frac{1}{3} \times \text{BDAE Threshold}$$

where the Bounded Dynamic Absolute Error (BDAE) Threshold = $\dfrac{\sum_{i\neq r}\Sigma_t \frac{|cr(t)\text{-}c_i(t)|}{N_T}}{N_{cluster}\text{-}1}$

Here, $c_r(t)$ = Observed value of representative day during time interval t; $c_i(t)$ = Observed value of non-representative day within the cluster during time interval t; $\tilde{c}_i(t)$ = Simulated performance measure during time interval t; N = Number of time intervals; and N_{cluster} = Number of days in the cluster representing this travel condition.

The above four criteria result in varying calibration targets based on the standard deviation of the observed data and the deviation between the observed data and simulated data. Criteria I and II in the above four criteria are referred to as the Variation Envelope criteria. These two criteria define two envelopes representing two ranges of the deviation of the values of each calibration MOE relative to the values of the MOEs estimated based on real-world data for the representative day of the modeled scenario. The envelopes are calculated based on the standard deviation of the day-to-day variation of the MOE values estimated for each 15-minute interval in the modeled period. Criteria I, referred to as the two-sigma criteria, is based on the calculation of a wider envelope of the deviations from the representative day values that are equal to 1.96 multiplied by the standard deviations of the measure. The FHWA method specifies that 95% of the simulated measures fall within this envelope. Criteria II, referred to as the one-sigma criteria, is based on the calculation of a narrower envelope of the deviation from the representative day values that equal to one standard deviation. The FHWA method specifies that two-thirds of the simulated measures should fall within this envelope. Criteria I and II corresponds to the currently used criteria by state agencies in that they calculate the acceptable targets for the deviations between real-world measurements and simulation measurements. Thus, this paper focuses on comparing the targets calculated Criteria I and II with the currently used fixed values.

Criteria III and IV in the above-mentioned four criteria compare the simulation output with a parameter referred to as Bounded Dynamic Absolute Error (BDAE), which reflects the deviation between the representative day and all non-representative days in a group of days that are grouped as one scenario to be modeled in the simulation effort (Wunderlich et al., 2019). Criterion III specifies that the average absolute deviation of simulated measure values from the real-world values of the representative day should be within the target BDAE threshold. Criterion IV specifies that the absolute value of the average of the deviations of each simulated measure values from the real-world values of the representative day should be less than one-third of the BDAE threshold.

3.11.6 Data Collection and Processing

The utilized case study in the investigation of the calibration targets is an I-95 facility segment in Broward County, Florida, and Palm Beach County, Florida. This segment has a length of 34.3 miles, three general-purpose lanes, one express lane in each direction, and 23 interchanges, as shown in Figure 3-8.

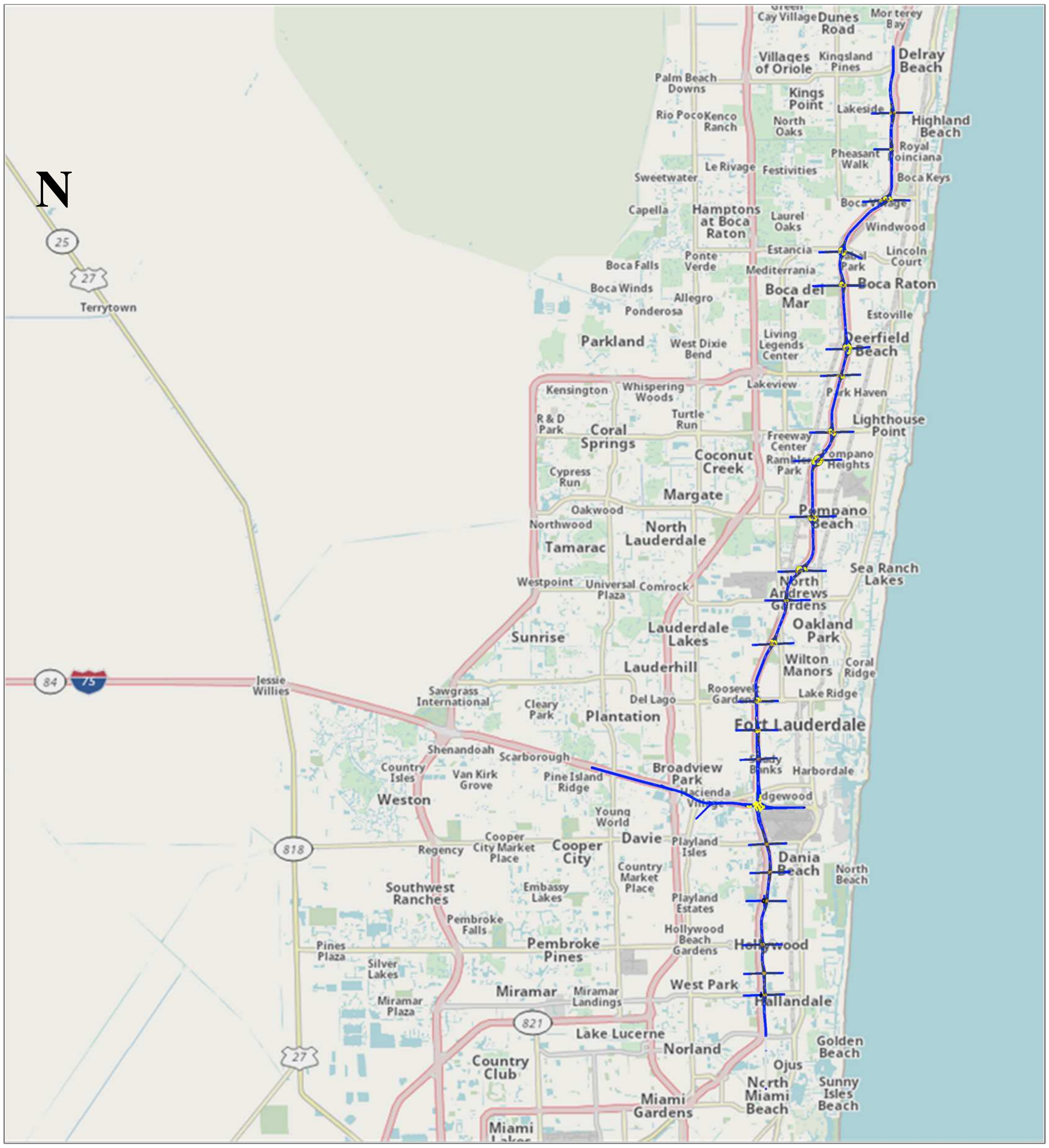


Figure 3-8 The I-95 freeway corridor in Broward and Palm Beach County, Florida

The traffic volume and speed data were collected for both directions of travel and both peaks based on archived data collected from point traffic detectors installed, operated, and maintained by the FDOT Transportation System Management and Operations (TSM&O) program. The detectors provide traffic volume, speed, and occupancy measurements. The traffic management centers (TMCs) in Florida calculate the travel time for each segment between the traffic sensors based on the speed measurements of the sensors at both ends of the segment, assuming that the speed measurements from each detector represent the speed of a segment that covers half the distance to the adjacent detector. The FDOT archives the measured volumes, measured speeds, and calculated travel times, and this data archive, also known as FDOT's central data warehouse, is used in this study by downloading data through the Regional Integrated Transportation Information System (RITIS) (FDOT, 2022a; RITIS, 2022). Since the quality of the data is important to ensure the accuracy of the calculated standard deviations, which is critical to the calculation of the targets, additional examination of the data quality was conducted using recommended data quality checking techniques. This study segmented the I-95 corridor into subsegments or links that connect the interchange locations, and the travel times were assigned to these links using the traffic detector speed data based on the same method used by the TMC, as described above.

As stated earlier, the 2019 FHWA Traffic Analysis Toolbox Volume III (Wunderlich et al., 2019) calibration method recommends selecting a single representative day for each modeled travel condition (scenario). If a multiscenario analysis is used, the different scenarios are identified using cluster analysis before identifying the representative day for each scenario. Depending on the simulation project's objectives, the modeled scenarios can include event-free days with various congestion levels. It can also include days with events such as incidents, severe weather, and/or construction events. In this research, only event-free weekdays are utilized in the comparison.

This study utilized the event-free days after removing weekends and weekdays with precipitation and incidents from the entire year's data. The results in the "Volume Target Comparison" and "Travel Time Target Comparison" presented in the section entitled "Results with Grouping All Event-Free Days in One Group" are based on an analysis that groups the event-free days into one cluster. The analysis in that section is presented using only one scenario for each of the two peak periods representing the peak periods of a typical day, as is used in most current real-world simulation applications. In most current simulation efforts, a single scenario is modeled for each peak period that represents "typical days" with no incidents and non-recurrent events. The representative day for the modeled scenario for each peak period was selected in this study using the methodology presented in the FHWA Traffic Analysis Toolbox Volume III (Wunderlich et al., 2019). However, as described later, the results from grouping all event-free days in one group indicated that the standard deviations of the MOEs of some of the links are high, indicating the need for further clustering of the normal days, as recommended by the 2019 FHWA methodology. An additional exploration was performed to cluster the normal days into three clusters, as explained later in this paper.

The representative day for each scenario selected for analysis was obtained based on the representativeness-distance $(\overline{\boldsymbol{d}})$ that is calculated as the average of all the distances between each individual day and the most representative day using the equation presented in the FHWA Traffic Analysis Toolbox Volume III (Wunderlich et al., 2019), as listed below. Given that $m_{i,j}(t)$ is a value of a measure like travel time on time interval t in day i at link j for a cluster of $N_{cluster}$ days; then, the average time-variant value of that measure for each time interval and links across all days in the cluster is calculated as:

$$\bar{m}_{t,j} = \frac{\sum_i m_{i,j}(t)}{N_{cluster}} \forall m, t, j \qquad (1)$$

The representativeness-distance $(\bar{\boldsymbol{d}})$ of a particular day is calculated as:

$$\bar{d} = \frac{\sqrt{\left(\bar{m}_{t,j} - \bar{m}_{t,j(t)}\right)^2}}{\bar{m}_{t,j}} \qquad (2)$$

Finally, the individual day (i*) that has the minimum $\bar{d}$ considering all links and measures are selected as the representative day as follows:

$$i^* = min_i\left[\Sigma_m \Sigma_i \Sigma_t \, \bar{d}\right] \qquad (3)$$

3.11.7 Results with Grouping All Event-Free Days in One Group

This section presents the results of the comparison of the calibration targets corresponding to the variation envelops as calculated using the method presented in the Traffic Analysis toolbox Volume III (Criteria I and II) with the fixed targets used by the states and focusing on the criteria used by FDOT, IDOT, and ODOT, as examples of the criteria used by the states. The comparison is performed using the data collected for the freeway case study.

Volume Target Comparison

The FDOT, IDOT, and ODOT calibration guidance specifies that 85% of the simulated volume should be within 400 vph of the field volume for link volumes of 2,700 vph or more. For all of the links of the limited access facility used as a case study in this paper, the link volumes were more than 2,700 vph, as it had four to six lanes with volumes ranging from 900 vehicles/15-min (3,600 vph) to 2,875 vehicles/15-min (11,500 vph). Thus, the 400 vph target is applicable when utilizing the states' guidance.

Table 3-7 shows examples of the results of the comparison between the volume targets calculated according to the state's criterion mentioned above and the dynamic volume targets calculated using the FHWA method for the northbound direction of the I-95 facility used as a case study. The examples are presented for two 15-minute intervals (from 5:00 p.m. to 5:15 p.m. and from 6:00 p.m. to 6:15 p.m.). The results for the southbound direction and the other periods are similar, so they are not presented in this paper due to space limitations. For each of the two 15-minute periods, the links in Table 3-7 are sorted from the link with the lowest standard deviation to the link with the highest standard deviation of volume.

Table 3-7 Comparison of the results from applying the varying threshold and fixed threshold methods to calculate volume calibration targets

Volume Measurements (5:00-5:15 pm))						Volume Measurements (5:00-5:15 pm)					
Links	Field Data*, veh/15-min	Standard Deviation, veh/15-min	2σ (vph, % of volume)	1σ (vph, % of volume)	400 vph (vph, % of volume)	Links	Field Data*, veh/15-min	Standard Deviation, veh/15-min	2σ (vph, % of volume)	1σ (vph, % of volume)	400 vph (vph, % of volume)
Atlantic Blvd	1074	45	351, 8%	179, 4%	400, 9%	Atlantic Blvd	1322	63	492, 9%	251, 5%	400, 8%
Commercial Blvd	1751	56	441, 6%	225, 3%	400, 6%	SW 10th St	1567	69	538, 9%	274, 4%	400, 6%
Cypress Creek Rd	1817	65	510, 7%	260, 4%	400, 6%	Davie Blvd	1280	76	594, 12%	303, 6%	400, 8%
Davie Blvd	1336	69	543, 10%	277, 5%	400, 7%	I-595	1490	76	597, 10%	305, 5%	400, 7%
I-595	1462	75	590, 10%	301, 5%	400, 7%	Glades Rd	1075	85	664, 15%	339, 8%	400, 9%
Congress Avenue	1735	94	737, 11%	376, 5%	400, 6%	Hillsborough Blvd	1934	106	827, 11%	422, 5%	400, 5%
Copans Rd	1635	98	768, 12%	392, 6%	400, 6%	Commercial Blvd	1871	109	851, 11%	434, 6%	400, 5%
SW 10th St	1516	109	854, 14%	436, 7%	400, 7%	Cypress Creek Rd	1942	112	880, 11%	449, 6%	400, 5%
Linton Blvd	2090	117	917, 11%	468, 6%	400, 5%	Copans Rd	1732	114	893, 13%	456, 7%	400, 6%
Sample Rd	1362	119	931, 17%	475, 9%	400, 7%	Congress Avenue	1669	117	915, 14%	467, 7%	400, 6%
Oakland Park Blvd	1788	122	954, 13%	487, 7%	400, 6%	Sunrise Blvd	1829	130	1016, 14%	519, 7%	400, 5%
Yamato Rd	1462	130	1021, 17%	521, 9%	400, 7%	Yamato Rd	1389	130	1018, 18%	519, 9%	400, 7%
Palmetto Park Rd	981	139	1090, 28%	556, 14%	400, 10%	Palmetto Park Rd	911	134	1048, 29%	535, 15%	400, 11%
Sunrise Blvd	2134	148	1163, 14%	594, 7%	400, 5%	Sample Rd	1195	144	1127, 24%	575, 12%	400, 8%
Glades Rd	969	151	1182, 30%	603, 16%	400, 10%	Oakland Park Blvd	1921	152	1190, 15%	607, 8%	400, 5%
Hillsborough Blvd	1921	216	1692, 22%	863, 11%	400, 5%	Linton Blvd	1926	153	1202, 16%	613, 8%	400, 5%
Broward Blvd	1369	297	2325, 42%	1186, 22%	400, 7%	Broward Blvd	1381	275	2154, 39%	1099, 20%	400, 7%

*Field data reference volume data measured in the identified representative day

Table 3-7 shows that 5 out of the 17 links (29.41%) between 5:00 p.m. and 5:15 p.m. and 5 out of the 17 links (29.41%) between 6:00 p.m. and 6:15 p.m. had a standard deviation equal to or below 85 vehicles per 15 minutes. Under these conditions, the 400 vph requirement falls between the one-sigma and two-sigma values in most cases. Since the states require 85% of the links to be within 400 vph and the FHWA method requires that 67% of the links be within one-sigma and

95% of the links to be within two-sigma, it appears that the states' calibration target is to some extent comparable to the targets calculated based on the FHWA method for standard deviations lower than 85 vehicles per 15 minutes.

The one-sigma criterion equals exactly 400 vph (the fixed target) when the standard deviation is 100 vehicles per 15 minutes, and the FHWA guidance requires that 67% link to be within this one-sigma. Thus, the examined fixed threshold criterion that requires 85% of the links to be within the 400 vph is more conservative for links that have standard deviations around this value. With further increases in the standard deviation, the increase of the calculated target above the fixed target increases and reaches unreasonably high values for some links. As stated earlier, the analysis in this section assumes that all of the event-free days belong to one traffic pattern. It can be seen from Table 3-7 that this assumption results in high standard deviation and thus wide variation envelopes when using the FHWA for some of the locations (such as the interchange in the vicinity of Broward Boulevard), producing wide variation envelops, allowing large deviation from real-world data when calculating the calibration targets. The high standard deviations indicate that clustering of the data should be conducted as recommended in the FHWA methodology to have more than one event-free operational scenario. This is expected to result in a lower standard deviation in each cluster compared to the standard deviation of the whole data. Such clustering is investigated later, as discussed in the "Results with Further Clustering of Event-Free Days" section.

Travel Time Targets

The FDOT, IDOT, and ODOT specify that the simulated travel times (TT) for 85% of the links should be within ±1 minute of the field travel times if a link's travel time is less than or equal to 7 minutes and within 15% if a link's travel time is more than 7 minutes. For all of the links of the facility used as a case study, the link travel times were less than 7 minutes. Thus, the ±1 minute criterion is applicable when using state guidance.

Table 3-5 shows examples of the comparison between the travel time targets calculated according to the FHWA method and the one-minute criterion of state agencies. The examples are presented for two 15-minute intervals for the northbound direction (from 5:00 p.m. to 5:15 p.m. and from 6:00 p.m. to 6:15 p.m.). For each of the two periods, the links in

Table 3-5 are sorted from the link with the lowest standard deviation to the link with the highest standard deviation of travel time. The results for the southbound direction and the other periods are similar, so they are not presented in this paper due to space limitations.

The FHWA method specifies that 67% of the link volumes are within one standard deviation (one sigma), and 95% of the link volumes are within two standard deviations (two sigma). The results in

Table 3-5 show that between 5:00 p.m. and 5:15 p.m., 50% of the links (8 out of the 17 segments) have one sigma less than or equal to 23 seconds and two sigma less than 46 seconds. A total of 71% of the links (12 out of the 17 segments) have one sigma less than or equal to 32 seconds and two sigma less than 63 seconds. A total of 76% of the links (13 out of 17) have one sigma less than 35 seconds and two sigma less than 70 seconds. The above results indicate that the specification of the one-minute criterion appears to be less conservative when compared to thresholds calculated using the FHWA method, as only the links with higher standard deviation have two-sigma values of more than 60 seconds. A reason for this might be that the examined links were short with short travel times. A total of 15 of the 16 travel times of the studied links ranged between 41 seconds and 155 seconds in the two periods. The fixed threshold of the one-minute target for links with travel times less than or equal to 7 minutes seems to be much less restrictive for links with short travel times, such as 41 seconds, compared to links with longer travel times close to 7 minutes. This issue with the one-minute target is expected to depend on the travel times and standard deviations of the travel times of the examined links. The conclusion can be different for segments with travel times that are higher and closer to the 7-minute threshold.

Table 3-8 Comparison of the results from applying the varying threshold and fixed threshold methods to calculate travel time calibration targets

Travel Time Measurements (5:00-5:15 pm)						Travel Time Measurements (5:00-5:15 pm)					
Links	Field Data*, seconds	Standard Deviation, seconds	2σ (seconds, %)	1σ (seconds, %)	1 minute (seconds, %)	Links	Field Data*, seconds	Standard Deviation, seconds	2σ (seconds, %)	1σ (seconds, %)	1 minute (seconds, %)
Congress Avenue	65	5	10, 16%	5, 8%	60, 93%	Congress Avenue	61	8	16, 27%	8, 14%	60, 98%
Linton Blvd	71	6	11, 16%	6, 8%	60, 84%	Davie Blvd	41	12	24, 59%	12, 30%	60, 145%
Davie Blvd	42	16	31, 73%	16, 37%	60, 143%	SW 10th St	56	16	32, 57%	16, 29%	60, 108%
Yamato Rd	107	17	33, 31%	17, 16%	60, 56%	Linton Blvd	69	18	35, 51%	18, 26%	60, 87%
Cypress Creek Rd	103	17	33, 32%	17, 16%	60, 58%	I-595	86	18	35, 41%	18, 21%	60, 69%
Commercial Blvd	139	19	37, 27%	19, 14%	60, 43%	Copans Rd	58	22	43, 74%	22, 38%	60, 104%
Copans Rd	60	19	37, 62%	19, 32%	60, 99%	Yamato Rd	133	24	46, 35%	24, 18%	60, 45%
I-595	87	23	46, 52%	23, 27%	60, 69%	Hillsborough Blvd	126	27	53, 42%	27, 21%	60, 48%
Atlantic Blvd	105	27	53, 50%	27, 26%	60, 57%	Sample Rd	126	29	57, 45%	29, 23%	60, 48%
SW 10th St	56	27	53, 94%	27, 48%	60, 107%	Palmetto Park Rd	68	30	59, 86%	30, 44%	60, 88%
Oakland Park Blvd	144	28	54, 38%	28, 19%	60, 42%	Commercial Blvd	108	31	61, 56%	31, 29%	60, 56%
Sunrise Blvd	145	32	63, 43%	32, 22%	60, 41%	Cypress Creek Rd	100	32	64, 64%	32, 33%	60, 60%
Sample Rd	155	33	64, 41%	33, 21%	60, 39%	Atlantic Blvd	106	33	66, 62%	33, 31%	60, 56%
Broward Blvd	75	36	70, 94%	36, 48%	60, 80%	Sunrise Blvd	137	35	69, 51%	35, 26%	60, 44%
Glades Rd	245	39	76, 31%	39, 16%	60, 24%	Broward Blvd	71	40	78, 110%	40, 56%	60, 85%

Travel Time Measurements (5:00-5:15 pm)						Travel Time Measurements (5:00-5:15 pm)					
Links	Field Data*, seconds	Standard Deviation, seconds	2σ (seconds, %)	1σ (seconds, %)	1 minute (seconds, %)	Links	Field Data*, seconds	Standard Deviation, seconds	2σ (seconds, %)	1σ (seconds, %)	1 minute (seconds, %)
Hillsborough Blvd	130	48	93, 72%	48, 37%	60, 46%	Oakland Park Blvd	96	40	79, 82%	40, 42%	60, 62%
Palmetto Park Rd	114	51	100, 88%	51, 45%	60, 53%	Glades Rd	223	59	115, 52%	59, 26%	60, 27%

*Field data reference volume data measured in the identified representative day

3.11.8 Results with Further Clustering of Event-Free Days

This study also investigated the impact of separating the traffic conditions into multiscenarios, as suggested in the methodology of FHWA Toolbox Volume 3, on the calculated thresholds. This investigation was conducted using a segment with five interchanges from Davie Road to Cypress Creek Road on the I-95 freeway corridor, which was used as a clustering case study in this project. This segment was selected due to its high traffic volume compared to the other segments of the network. The K-means clustering method was applied to separate the traffic conditions into three clusters based on the selected segment's volume and travel time data. The calibration thresholds were calculated for each cluster and compared with the thresholds for the whole dataset of normal (event-free) days without clustering. It should be noted that incidents and bad weather days were not included in the investigation.

As observed in Table 3-9, the standard deviation without clustering is significantly higher than the standard deviation with clustering. It indicates that the separation of the traffic conditions into clusters will result in thresholds that are tighter, compared to those calculated without clustering. However, the FHWA approach has not provided a detailed methodology to decide on the number of clusters that are used as operational scenarios in the analysis. Additional guidance is needed on the minimum number of clusters since this will affect the calculation targets and thus the quality of the calibration.

Table 3-9 Variable threshold envelopes based on clustering analysis

Clusters	Date	Time	Mean of Field Volume (veh/15-min)	Mean of Field Travel Time Mean (seconds)	1σ of Volume (vph)	1σ of Travel Time (seconds)
Cluster 1	7/10/2015	16:30:00	1713	59.17	194	4.62
Cluster 1	7/10/2015	16:45:00	1711	56.97	129	5.12
Cluster 1	7/10/2015	17:00:00	1673	54.33	204	5.21
Cluster 1	7/10/2015	17:15:00	1747	54.62	222	5.06
Cluster 1	7/10/2015	17:30:00	1772	53.52	261	5.19
Cluster 1	7/10/2015	17:45:00	1744	55.04	197	5.48

Clusters	Date	Time	Mean of Field Volume (veh/15-min)	Mean of Field Travel Time Mean (seconds)	1σ of Volume (vph)	1σ of Travel Time (seconds)
Cluster 1	7/10/2015	18:00:00	1749	60.71	198	5.11
Cluster 1	7/10/2015	18:15:00	1776	62.48	168	4.50
Cluster 2	5/1/2015	16:30:00	1884	55.61	263	5.52
Cluster 2	5/1/2015	16:45:00	1858	54.87	175	4.48
Cluster 2	5/1/2015	17:00:00	1858	56.95	157	5.19
Cluster 2	5/1/2015	17:15:00	1860	54.51	193	4.67
Cluster 2	5/1/2015	17:30:00	1781	53.30	225	4.88
Cluster 2	5/1/2015	17:45:00	1774	53.68	272	5.64
Cluster 2	5/1/2015	18:00:00	1751	56.85	228	6.18
Cluster 2	5/1/2015	18:15:00	1735	60.66	223	5.64
Cluster 3	2/13/2015	16:30:00	1881	42.18	278	3.86
Cluster 3	2/13/2015	16:45:00	1753	41.16	242	3.24
Cluster 3	2/13/2015	17:00:00	1836	42.16	182	3.46
Cluster 3	2/13/2015	17:15:00	1743	36.89	319	3.89
Cluster 3	2/13/2015	17:30:00	1736	36.78	303	5.34
Cluster 3	2/13/2015	17:45:00	1746	37.72	323	6.25
Cluster 3	2/13/2015	18:00:00	1854	40.28	445	7.42
Cluster 3	2/13/2015	18:15:00	1712	36.96	360	9.71
Non-clustered	9/3/2015	16:30:00	1869	70.45	309	14.29
Non-clustered	9/3/2015	16:45:00	1862	71.01	320	13.83
Non-clustered	9/3/2015	17:00:00	1870	73.84	321	14.60
Non-clustered	9/3/2015	17:15:00	1801	76.38	305	15.18
Non-clustered	9/3/2015	17:30:00	1849	74.05	322	15.58
Non-clustered	9/3/2015	17:45:00	1847	72.01	292	17.63
Non-clustered	9/3/2015	18:00:00	1831	66.32	327	17.29
Non-clustered	9/3/2015	18:15:00	1892	59.69	302	17.42

3.11.9 Conclusion

This study compares the results from using calibration targets that vary depending on the day-to-day variations in the MOEs of a segment as proposed in the FHWA methodology with fixed targets recommended in state DOT guidelines. In doing so, this study hopes to motivate efforts in an area of research that is critical for enhancing the capability of agencies to perform traffic simulation analysis. Such research is long overdue.

The review of state guidance indicates that the calibration targets used by different states have similarities in some cases and differences in others. In at least some of the cases, they seem to be based on previous use of unjustified calibration targets in the early 2000s. This further confirms the need to examine the calibration targets. The literature review indicates that, surprisingly, very little work has been done in this area.

The development of the 2019 FHWA simulation calibration methodology provides an opportunity to revisit state guidance. There is also a need to examine the application of the FHWA simulation calibration under different scenarios. Such examination will provide much-needed experience and lessons learned regarding the effectiveness and ease of use of the FHWA method.

The practical application of the FHWA's varying calibration target method possesses several data challenges, including the availability of data for freeways and even more on arterials and the accuracy of the collected data. Using targets that vary depending on data analysis may also be less understandable and acceptable to some agencies that now have to deal with the uncertainty in the quality of data analysis and varying thresholds for different projects and locations for each project. In addition, the quality of the data from traffic sensors can impact the calculated standard deviations, which in turn will impact the accuracy of the calculated targets. Thus, the analysts should ensure the quality of the utilized data before using it in calculating the targets.

The study compared a fixed target for volume calibration used by three state agencies with the varying targets calculated using the FHWA methodology for the freeway facility used as a case study. The results indicate that the examined state calibration target is comparable to the calculated targets calculated based on the FHWA method when the standard deviation of the link volume is relatively low (below 85 vehicles per 15 minutes). However, the states' calibration target becomes more conservative when the standard deviation is higher, and this difference increases with the increase in the standard deviation. The study also found that the fixed travel time target appears to be less restrictive compared to the targets calculated using the FHWA methodology for freeway links with relatively short travel times and lower standard deviations, as is in the case study. However, the conclusion could be different for segments with higher travel times and lower standard deviations.

The analysis in this study indicates that assuming that the event-free days belong to one pattern can result in high standard deviations of the MOEs of some of the links, resulting in large acceptable deviations between the simulation results and real-world measurements. Thus, further clustering of the event-free days into more than one pattern is recommended when applying the FHWA methodology, when the standard deviations of the performance measures are high. The study results confirm that such clustering can produce tighter acceptance thresholds. Additional guidance is needed regarding the number of clusters to use in identifying the operational scenarios. The more are the number of clusters, the lower is the standard deviation and thus the tighter are the acceptance thresholds.

The analysis in this study was conducted using a freeway segment as a case study. Additional research is needed on arterial segments to better understand the applicability of FHWA's approach on arterials. In addition, research is needed to assess the impact of data quality from different sources on the acceptability of the calculated thresholds. Further analysis is needed on how the varying threshold methods impact and are impacted by advanced modeling approaches such as multiresolution analysis and multiscenario analysis, including varying demand levels, incidents, and weather conditions.

3.12 SELECTION OF TRAFFIC ANALYSIS DAY(S)

3.12.1 Introduction

An important step in analyzing traffic operations is how real-world data is collected, processed, and analyzed to identify the operational scenarios and the representative days for these scenarios. Most existing traffic analysis studies use one set of inputs to the analysis to represent one operational scenario for each analyzed peak period. With the availability of continuous data from traffic monitoring systems, the analysts in most cases take the averages of traffic volume, speed, travel time, and other measures and use these averages as inputs to the analysis. In some cases, when calculating the averages, the analysts only use data collected from the peak months of the year rather than the whole year. However, averaging the measures results in a synthetic day that does not occur in the real-world and produces values that can underestimate the actual congestion level in the system.

The identification of traffic patterns that best represent the traffic conditions is critical to the success of traffic analysis and the decisions made based on the analysis. In some efforts, particularly those for analyzing traffic conditions with traffic management and operations, analysts should perform the analysis for different operational conditions throughout the year, including different recurrent congestion levels, incident conditions, and bad weather conditions. In these efforts, traffic patterns that represent the varying traffic conditions will have to be identified for multiscenario analysis. However, even if the scope of the analysts is to only analyze one scenario representing typical traffic conditions, there is a need to analyze the variations in traffic conditions based on the data from multiple days to determine the day that best represent the traffic conditions. For example, assume that we have ten days that we collect the data for to make things simple. If five of the days have a travel time of one hour and five days have a travel time of half an hour, the average day has a travel time of 45 minutes. However, trying to calibrate the simulation for 45-minute simulation is not correct since such travel time was never observed in real-world conditions. The Federal Highway Administration (FHWA) Traffic Analysis Toolbox Volume III (Wunderlich et al., 2019) recommended the use of cluster analysis to categorize the traffic conditions in an entire year into a number of clusters and determine a representative day for each of these clusters. However, the above-mentioned reference did not provide detailed guidance on how to perform cluster analysis considering the many options available to the analysts and how to evaluate the quality of the resulting traffic patterns.

There are many decisions that need to be made when conducting the cluster analysis to obtain the representative day(s). This study identified three knowledge gaps that it addressed to support these decisions. First, there are various clustering algorithms and methods, each of which have their own strengths and weaknesses. There is a need to research and identify the abilities and performance of these algorithms in clustering the data obtained from a typical traffic monitoring systems. Second, it is not clear how the aggregation of the input variables in time and space can impact the quality of the clustering. For example, if the traffic volume used as input is averaged over the whole corridor of the study and for the whole analysis peak period, then important traffic patterns in time and in space might be lost and thus can reduce the quality of the results. Third, there is a need to investigate how the performance of the results from clustering of traffic conditions can be assessed considering the alternative methods and parameters than can be used.

This study presents and assesses methods and parameters to identify patterns and representative days of these patterns based on cluster analysis for use in traffic analysis of event-free conditions, which are conditions with no incidents, construction, weather, or other events. This study also proposes methods to assess the quality the results from clustering and representative day selection using various performance measures based on techniques reported in statistics literature as well as traffic engineering literature. Initially, this study compares the results from two widely used clustering algorithms – the K-means and Gaussian Mixture Model (GMM). Then, it compares the use of input variables aggregated for an entire facility and peak period versus using input variables that are segregated in time and space. The best representative days obtained based on clustering are compared with the average day as currently used in common modeling practices, in terms of their abilities to represent the event-free traffic conditions.

3.12.2 Literature Review

The FHWA Traffic Analysis Toolbox Volume 3 (Wunderlich et al., 2019) presented a procedure for multiscenario analysis, which involves the use of cluster analysis for the identification of the analysis scenarios. Cluster analysis is characterized as an unsupervised machine-learning technique that segments the objects under consideration into clusters, with the objects within each cluster having closer relations with each other compared to their relationships with objects assigned to other clusters (Hastie et al., 2009; He et al., 2011; Jingxin & Mei, 2007). Although the use of a clustering in the transportation engineering field has been limited, the interest in using this approach in the recent past has gained popularity to identify multiscenario prediction for transportation system analysis, management, and operations.

The focus of implementing a clustering technique to traffic data is to determine spatial and temporal patterns based on traffic measures, such as traffic volume, speed, and travel time. Ku et al. used K-means clustering algorithm and a subsequent deep learning-based neural network model to predict missing traffic volume counts (Ku et al., 2016). The utilized clustering categorized the traffic flow operations based on traffic density and speed data aggregated in 15-minute intervals. He et al. used nested clustering techniques to identify the operating scenarios of freeways (He et al., 2011). Park used the K-means and Fuzzy clustering algorithms to forecast traffic demand and analyze temporal and spatial travel behaviors (Park, 2002). Other studies used other clustering approaches such as the Fuzzy C-means clustering and spectral clustering for pattern recognition and analyzing traffic state variations on urban roads (Chen et al., 2017; Zhang et al., 2017). Several studies showed that the K-means clustering of historical data can be used to relate travel time variations to external factors such as weather conditions and traffic incidents (Al-Kaisy & Huda, 2022; Chen & Chien, 2001; Deb Nath et al., 2010; Wei & Lee, 2007; Wu et al., 2004). Hans et al. used clustering techniques to compute the probabilistic distributions of travel time on urban arterials (Hans et al., 2014).

One of the most recognizable implementations of clustering techniques in transportation system analysis is the FHWA's "Analysis, Modeling, and Simulation (AMS) Testbed for Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) Programs" effort (Vasudevan & Wunderlich, 2013). This effort involved six testbeds (San Mateo (US 101), Pasadena, Dallas, San Diego, Phoenix, and Chicago testbeds) that pilot-tested the use of AMS for assessing active traffic management and dynamic mobility applications. The six testbeds used clustering approaches that vary from one testbed to another to determine the analysis scenario. Alexiadis and Chu used AMS framework to evaluate the performance of integrated corridor management (ICM) deployment for diverse traffic operating conditions (Alexiadis & Chu, 2016). The study used clustering to group workdays with similar travel characteristics into clusters based on incident's day, time of the day, traffic direction, closed lane numbers, incident's duration, traffic flow, precipitation duration, and average travel time.

The K-means clustering method is a widely used technique that clusters data utilizing the Euclidian distance as the dissimilarity matrix (Huang, 1998). Other clustering approaches has been proposed that theoretically can provide advantages compared to similarity-based clustering techniques like the K-means clustering. The mixture distribution type of clustering involves data fitting and use of identified conditional probabilities of the clustered data points. One of the most widely used mixture models for clustering is the Gaussian Mixture Model (GMM) (Bishop, 2006). This study assessed the results of using the K-means and GMM to cluster traffic data, as presented later in this paper.

3.12.3 Methodology

This section describes the methods used to perform cluster analysis to investigate travel patterns represented by the available traffic data.

3.12.3.1 Utilized Data

The utilized case study in this study is an I-95 corridor segment in Broward County, Florida, and Palm Beach County, Florida. This segment has a length of 34.3 miles and 23 interchanges. The traffic volume and speed data were collected from point traffic detectors installed and operated by the Transportation System Management and Operations (TSM&O) program of the Florida Department of Transportation (FDOT). The study is based on time-variant data for the northbound (NB) direction during the PM peak period (4:30 PM to 6:30 PM), which was aggregated at 15-minute intervals. This study focused on determining distinguished traffic patterns in event-free or “normal” weekdays. Thus, the data for these days were segregated from the data for “abnormal” weekdays that have non-recurring events like incidents, weather events, and/or work zones. However, the investigation can be extended to include non-recurrent event days in the clustering process.

The attributes of each data point used as inputs to the analysis are date, time interval, location, traffic volume in vehicle per hour (vph), and travel time rate in seconds per mile (sec/mi). The volume and speed data are collected using detectors located at an average of half-mile intervals. The traffic management center calculates the travel time based on the speed data collected from the point detectors. These estimates are used in this study to calculate the travel time rates in seconds per mile. The volume and travel time measures are referred to as the “key measures” in this study since they are used by the cluster algorithms to group the data.

3.12.3.2 Investigated Clustering Algorithms

This study compares the use of the K-means and the GMM algorithms for the identification of traffic conditions for analysis. The K-means clustering partitions the dataset objects into “k” different clusters through an iterative process using simple distance from the cluster’s center to assign the cluster membership (Shi et al., 2010). The GMM is based on the Expectation-Maximization algorithm that uses Gaussian distribution in clustering. Unlike the K-means algorithm, which places a circle or a hyper-sphere around each cluster, the directions, and lengths of the axes of GMM's density contours are characterized by an ellipsoid. In theory, this is an advantage of the GMM algorithm since it can accommodate oblong clusters of any shape. If the shape of optimal clusters is not circular, then the data points of two different clusters can overlap each other when using the K-means algorithm due to the rigid (circular) nature of the algorithm. However, it is not clear if this provides an actual advantage when the GMM algorithm is applied to traffic data instead of the more widely used K-means algorithm.

3.12.3.3 Investigated Aggregation Levels

There is no clear guidance on how the data obtained from different locations along the analyzed facility can be aggregated in time and space. In investigating the impact of using segregated volume and travel time data in time and space, the study compared four levels of the aggregation of the data.

- *No segregation of the inputs:* The clustering is based on the average values of the traffic volume and travel time over the entire 34.3-mile facility and over the entire peak period (4:30 PM to 6:30 PM) without segregating the data of the facility into data for different segments in space and/or different time intervals, resulting in only two input variables: one for volume, and one for travel time.

- *Spatial segregation of the inputs:* With this level, the clustering is based on the average values of the traffic volumes and traffic travel times for three segments instead of the averages for the full length of the facility. The three segments were a result of dividing the 34.3-mile facility into sub-segments based on the locations of the major bottlenecks, and the differences in the congestion patterns and traffic demands between the three segments. This segregation was done considering that utilizing the average values for the whole segment can dilute the information required for identifying different traffic patterns. The spatial segregation resulted in three inputs to clustering for each of the two key measures instead of having one average input per measure for the full segment. The three segments are referred to in this study as Segment-1 or Location 1 (Hallandale Beach Blvd. to I-595), Segement-2 or Location 2 (Davie Rd. to Cypress Creek Rd.), and Segment-3 or Location 3 (Atlantic Blvd. to Linton Blvd.). The lengths of the first two segments are about 8 miles each, while the length of the third segment is about 17 miles. Segment-2 has the highest average traffic flow rate (8,206 vph), and Segment-3 has the lowest average traffic flow rate (5,788 vph) among the three segments.

- *Temporal segregation of the inputs:* With this segregation level, the two-hour peak period is divided into four 30-minute time slices, resulting in four inputs to clustering for each of the two key measures instead of one input per measure reflecting the whole period. This level does not involve spatial segregation of the data.

- *Spatial and temporal segregation of the inputs:* This level of segregation involves combining both the spatial and temporal segregation, as mentioned above. The measures are segregated both in time (four 30-minute periods) and space (three segments), resulting in a total of 12 inputs to clustering for each of the two key measures. This level presents the highest resolution of the key measures investigated in this study. The twelve input variables were given acronyms based on the location and the time periods. For example, at location 1, volume and travel time of the first 30-minute time slice of the analysis period is referred to as avg_vol1.1 and avg_TT1.1, respectively. For location 2 and time slice 3, the variables are referred to as avg_vol2.3 and avg_TT2.3.

3.12.3.4 Selection of the Number of Clusters

One significant step in any cluster analysis is to determine the optimal number of clusters to be used. This step ensures meaningful and interpretable clusters and avoids overfitting or underfitting of the data. There are several methods that determine the optimal number of clusters, including the Bayesian Information Criterion (BIC), typically used with the GMM clustering algorithm, and the and Elbow method, used with K-means clustering algorithm (Brownlee, 2019; Burnham & Anderson, 2004). The BIC statistics is calculated based on logistic regression by minimizing a certain score to select the optimal number of clusters (Brownlee, 2019). However, for a small sample size, the BIC is not an effective measure for selecting the optimal number of clusters (Burnham & Anderson, 2004). The Elbow method is a plot that depicts the total within clusters sum of squares (WCSS) for each tested number of clusters (k). The number of clusters, k, to be used in the cluster analysis is selected by identifying the point in the graph where further increases in the value of k no longer results in a significant decrease in the WCSS (Marutho et al., 2018). Table 3-10 shows the BIC score for the investigated clustering aggregation levels and different numbers of clusters when using the GMM algorithm. The lowest BIC score, shaded in Table 3-10, indicates the optimal number of clusters. Table 3-10 shows that the optimal number of clusters for no segregation is 3, spatial segregation is 3, temporal segregation is 2, and spatiotemporal segregation is 4. Interestingly, the Elbow method, used with the K-means algorithm, suggests the same optimal number of clusters (3 for no segregation, 3 for spatial segregation, 2 for temporal segregation, and 4 for spatiotemporal segregation). At the spatiotemporal aggregation level, the higher number of clusters is an indication that this clustering is better at identifying more distinctive patterns in the data, compared to other segregation levels.

Table 3-10 Optimal number of clusters using BIC score for GMM clustering algorithm with different aggregation levels

Aggregation Level	**BIC Score for Number of Clusters**		
	2	3	4
No Segregation	-57	-117	-102
Spatial Segregation	-120	-125	-50
Temporal Segregation	-420	-340	-230
Spatiotemporal Segregation	-375	-1200	-2000

Note: The shaded cell indicates the best BIC score.

3.12.3.5 Assessment of Clustering Quality

After performing the clustering, this study evaluated the quality of clustering using the performance measures reported in the statistics literature and traffic engineering literature, as described in this section.

Performance Measures from Statistic Literature

Several internal clustering validation metrics have been proposed in statistics literature to assess the quality of the clustering results including the Silhouette Coefficient (SC), Calinski-Harabasz Index (CH), and Davies-Bouldin Index (DB) (Liu et al., 2013). However, these measures have an issue in that they are dependent on the dimensionality of the data, meaning that for larger numbers of parameters, these measures identify data points as outliers even though the data points could be a part of a cluster (Platzer, 2013). Another method that does not have this issue is the t-Distributed Stochastic Neighbor Embedding (t-SNE) visualization method. The t-SNE method allows visualizing the difference between different aggregation levels of the investigated dataset (Azimi & Zhang, 2010). The t-SNE is a non-linear dimensionality reduction technique that uses an unsupervised learning algorithm. It attempts to place similar data points close to each other while preserving the global structure of the dataset (Lowry, 2014).

In this study, the t-SNE visualization method is used to visualize the performance of the investigated clustering algorithms and aggregation levels (Al Mamun et al., 2021). The utilization of the t-SNE as a statistical performance measure avoids the limitations of the internal clustering validation metrics, such as the SC, CH, and DB, mentioned above.

Performance Assessment Techniques Derived based on Traffic Engineering Literature

Researchers have also proposed methods for assessing the results from cluster analysis based on traffic engineering concepts. For example, Azimi and Zhang (Azimi & Zhang, 2010) observed the distribution of the performance measures of different clusters by plotting speed versus flow (fundamental diagram) data to identify the performance of the clusters. In addition to the t-SNE visualization method recommended in the statistics literature, this study explores the use of measures reported in traffic engineering literature to quantify the quality of clustering of the collected traffic data.

Sum of Representative Day Distances

The FHWA Traffic Analysis Toolbox Volume III proposed a methodology for identifying a single representative day for each cluster resulting from clustering of the time-variant data. This representative day is defined as the individual day with the minimal distance between the values of the key measures (such as volume and travel time) for that day from the corresponding values of these measures for all days in the cluster (Wunderlich et al., 2019). This study adopts this representative day distance to calculate a variable, referred to in this study as the Sum of the Representative Day Distances, which measures how close the representative days of the identified clusters are to all days in all clusters. In calculating this variable, first the representative day distance is calculated for each cluster for each key measure used in clustering as follows.

$$\dot{m}_{k,i,n} = \frac{|m_{k,i,n} - m_{k,n}|}{m_{k,n}} \tag{1}$$

where,

$\dot{m}_{k,i,n}$ = difference between the value of a key measure k in the representative day and the value observed in day i of cluster n,

$m_{k,i,n}$ = value of a key measure k in day i in cluster n, and

$m_{k,n}$ = value of a key measure k in the representative day of cluster n.

Next, the resulting values from Equation 1 are summed over all key measures as follows.

$$d_{i,n} = \sum_k \dot{m}_{k,i,n} \tag{2}$$

where,
$d_{i,n}$ = distance between each individual day i in cluster n and the corresponding representative day.

Finally, the Sum of Representative Day Distance ($\bar{d}$) is calculated as the average of all the distances $d_{i,n}$ between each individual day and the representative day of all clusters, calculated in the previous step.

$$\bar{d} = \frac{\sum_n \sum_i d_{i,n}}{N_{days}} \tag{3}$$

where,
$\bar{d}$ = Sum of Representative Day Distance, and
N_{days} = total number of clustered days.

Fundamental Diagram

This study also uses a macroscopic fundamental diagram for each cluster to visualize the relationship between traffic flow and speed for each of the three subsegment (Geroliminis & Sun, 2011). The horizontal and vertical axes represent the volume (vehicles per 30 minutes) and speed (miles per hour, mph), respectively. In this study, the data points of speeds and volumes of the identified representative days for each 30-minute period are highlighted on the fundamental diagram to visualize the change in travel conditions between the identified days relative to the traffic conditions for all days in the analysis.

Heat Map

The heat map is a two-dimensional visualization technique that shows the variation in the magnitude of a variable as variation in color by hue or intensity (Zhao et al., 2014). Heat maps are used in this study to visualize the traffic patterns generated for each cluster generated using a given clustering approach. Each point on the horizontal axis in the utilized maps represents a day belonging to a given cluster. In the heat maps, the key measures within each cluster are visualized through a changing color scheme, with the red color indicating high traffic volume or high travel time; green representing low traffic volume or low travel time, and yellow representing medium traffic volume and travel time.

3.12.4 Results and Discussion

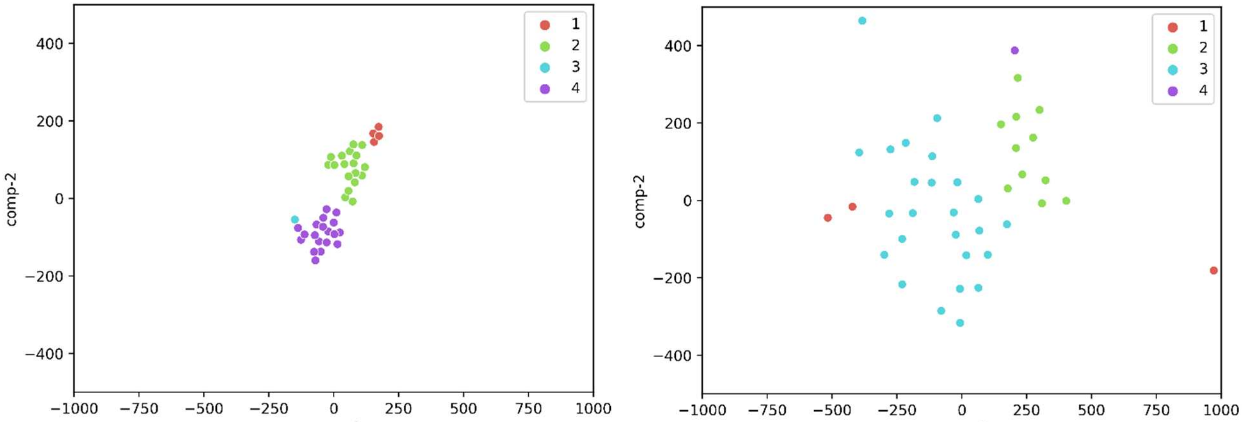
This section discusses the results of clustering using different algorithms and aggregation levels. The clustering results are assessed based on performance assessment techniques, discussed in the previous section. In addition, the selected representative days obtained based on the clustering are compared with the average day used in current analysis practices in terms of their abilities to represent the event-free traffic conditions in a year.

3.12.4.1 Assessment of Clustering based on Measures from Statistic Literature

Figure 3-9 and Figure 3-10 show the t-SNE projections. The x-axis and y-axis, referred to as comp-

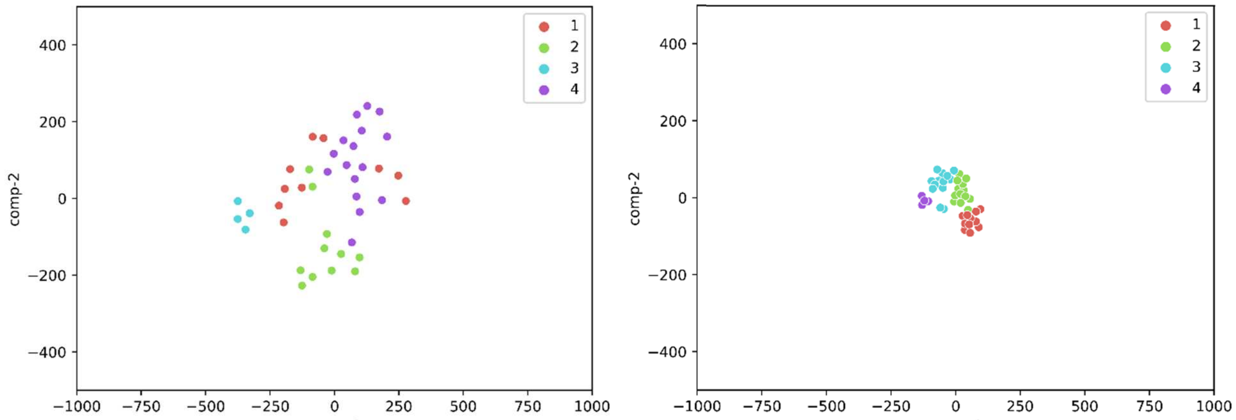
1 and comp-2, indicate the relative distances between the data points. The t-SNE visualization in these figures is used as a visual representation that enables an intuitive evaluation and the detection of issues with clustering. Noting the different number of input parameters involved in each aggregation level (no segregation has 2 parameters, spatial segregation has 6, temporal segregation has 8, spatiotemporal segregation has 24), the t-SNE visualization enables the comparison of clustering, using these aggregation levels, in the same dimensions (two dimensions). If the clusters are well-separated and appear to be compact and coherent, this indicates good clustering. However, if there are overlaps between clusters, if there appears to be outliers that are very far from the cluster center, or if the datapoints belonging to the same cluster appear to be distant and not as compact, then these are all signs of poor clustering (Van der Maaten and Hinton, 2008).

Figure 3-9 shows the t-SNE projections for different aggregation levels for the same clustering algorithm (the K-means algorithm) and same number of clusters (four). Figure 3-9, the data points in the four clusters are displayed in different colors (for the comparison of the results of clustering using different aggregation levels. Figure 3-9 (d) shows that the best clustering is obtained with the spatiotemporal segregation level. Compared to other clustering levels shown in Figure 3-9 (a), Figure 3-9 (b) and Figure 3-9 (c), the spatiotemporal segregation level in Figure 3-9 (d) shows a clearer separation of the data points of different clusters and it gives the most compact clusters, indicating better clustering of the data points.



(a) No Segregation K-means 4 clusters

(b) Spatial Segregation K-means 4 clusters

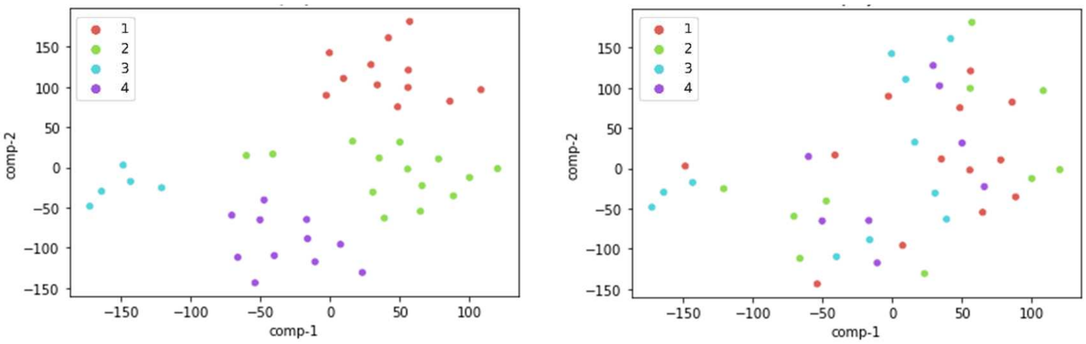


(c) Temporal Segregation K-means 4 clusters

(d) Spatiotemporal Segregation K-means 4 clusters

Figure 3-9 t-SNE Projections to compare the different aggregation levels

The results from using the two clustering algorithms, the K-means and GMM are compared in Figure 3-10. In this case, the same number of clusters (four) and the same segregation level (spatiotemporal segregation) were used. Figure 3-10 (a), which represents the K-means algorithm, shows evenly clustered data, while Figure 3-10(b), which represents the GMM algorithm, shows significant overlaps in the data points from different clusters with no clear separation of the data points for different clusters. In the upcoming sections, the GMM algorithm is ruled out based on the results of the projections in Figure 3-10. The above results could indicate that that K-means algorithm is more suitable for this type of data than GMM but this needs confirmation in future studies.



(a) Spatiotemporal K-means

Figure 3-10 t-SNE Projections to compare the K-means and GMM algorithms

Based on the analysis of the results of the t-SNE projections, it can be concluded that the K-means algorithm using the spatiotemporal aggregation level, with four clusters (as per the earlier results on the optimal number of clusters), provides the most distinctive clustering results with a better ability to group days that share similar travel conditions together.

3.12.4.2 Assessment of Clustering based on Techniques Derived based on Traffic Engineering Literature

This section compares different approaches to clustering based on selected measures and techniques derived from traffic engineering literature. These techniques include the Sum of Representative Day Distances, the heat map, and the fundamental diagram, as described earlier.

Sum of Representative Day Distances

The shorter is the Sum of Representative Day Distances, the better is clustering, since this indicates that all the days in the cluster are close to each other and close to their representative day. The Sum of Representative Day Distance, calculated according to Equations 1 to 3 for each aggregation level when using the K-means with four clusters indicates that clustering with the spatiotemporal segregation performed the best among all other segregation levels in providing the lowest Sum of Representative Day Distance (2.30). This value is significantly lower than the Sum of Representative Day Distance when using the average day of all days (3.13) or average day of peak months (3.81), indicating better representation of the traffic conditions with the utilization of the representative days based on clustering. The distances for the remaining aggregation levels are 2.81 for no segregation, 2.53 for spatial segregation, and 2.61 for temporal segregation.

Fundamental Diagram

The macroscopic fundamental diagrams were plotted to examine the advantage of using clustering to select representative days for modeling compared to using the average values. For this purpose, this section presents the diagrams for event-free days for Segment-2, which connects the Davie Rd. interchange and Cypress Creek Rd. and has a length of about eight miles.

Figure 3-11 shows a color-coded traffic fundamental diagram with each color representing the data points of one of the four clusters obtained when using the spatiotemporal level of segregation. Figure 3-13 shows the same fundamental diagram with no indication of clustering. The comparison of the two diagrams is meant to indicate how taking average values of the traffic conditions as represented volume and speed measurements can dilute the results and reflect conditions that do not represent the critical conditions on the facility. As discussed in the following subsections, Figure 3-12 shows that the traffic conditions in the four 30-minute intervals of the peak periods of the representative days of two of the four clusters as represent by volume versus speed relationships are significantly more congested (speeds between 35 mph and 45 mph) compared to the corresponding values for the average day shown in Figure 3-13 (speeds between 45 mph and 55 mph for the average of February and March and 50 mph to 60 mph for the average of the whole year).

The fundamental diagram shows the directional volumes on the four-lane freeway segments per direction in vehicles per 30 minutes showing that the capacity of the segment is about 3,850 veh/30 minutes (7,300 vehicles per hour, which is 1,925 vehicles per hour per lane). The data for the representative day for each cluster are highlighted using numbers from 1 to 4. These numbers indicate the data points for the four 30-minute intervals, with “1” indicating the data point for the first interval in the peak period and “4” indicating the data point for the fourth interval in the peak period. The diagram indicates that both Cluster 1 and Cluster 4 are congested, but Cluster 4 is less congested, and the congestion in the representative day of Cluster 4 starts clearing in the last 30 minutes. Cluster 2 and Cluster 3 have relatively high speeds (55 to 65 mph versus 35 to 45 mph for the congested intervals of Clusters 1 and 4). However, Cluster 3 has much higher demands than Cluster 2, with volumes close to the capacity of the segment. It is interesting to see that although Clusters 1 and 4 have significantly lower speeds than Cluster 3, their volumes are also significantly lower, indicating that these clusters are on the congestion side of the fundamental diagram with the measured volumes constrained by the capacity of the bottleneck segments.

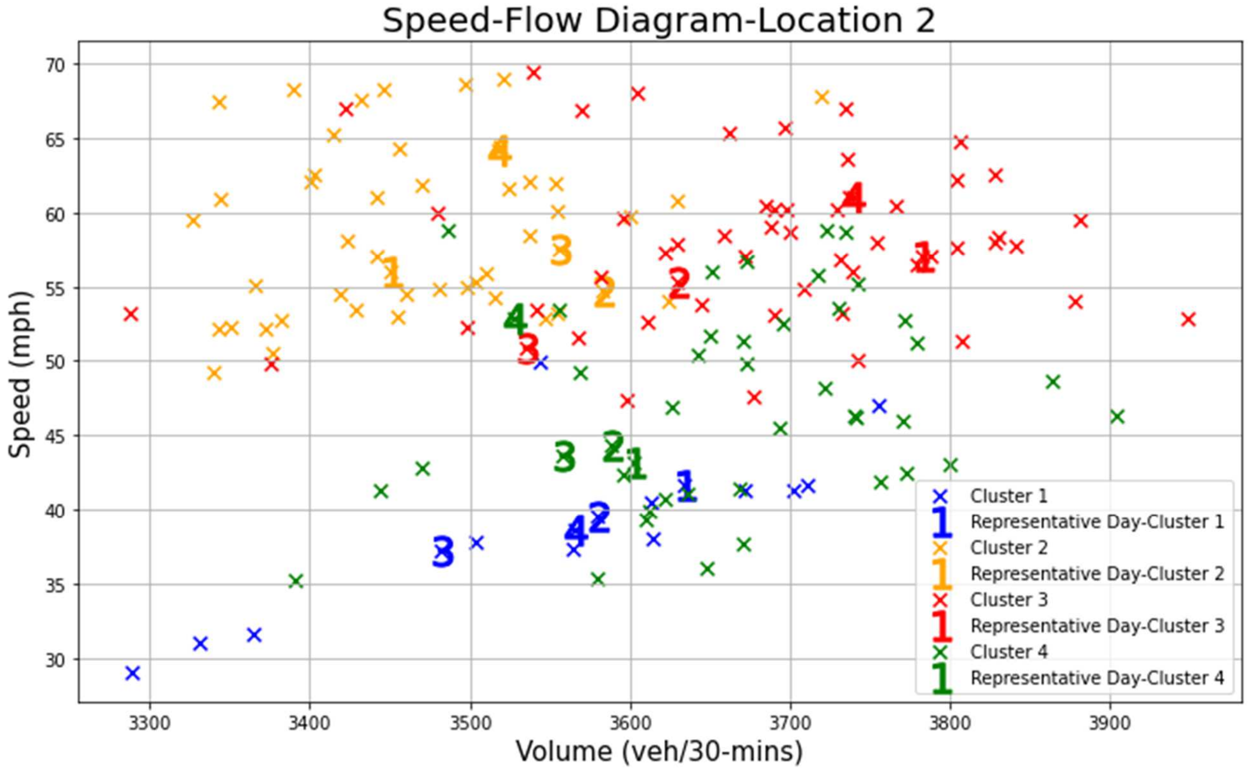


Figure 3-11 Traffic fundamental diagram with highlighted representative day data points for Segment 2 for four time slices

Figure 3-12 shows the same fundamental diagram as Figure 3-11, but this time with the highlighted data points with the interval numbers reflecting the average value for all days and the average values for the peak season (February and March). The average speed ranges from 52 mph to 55 mph when averaging the data points through the year, and from 47 mph to 54 mph when averaging the data for the peak season. However, the actual speed of a significant proportion of the actual data points is below 45 mph. Averaging the speed and volume values masked the fact that such days present since the low speeds are averaged with high speeds. On the other hand, as indicated in Figure 3-11, the speeds of the representative days range from 35 mph to 65 mph when using clustering, which indicates better coverage of the operational conditions.

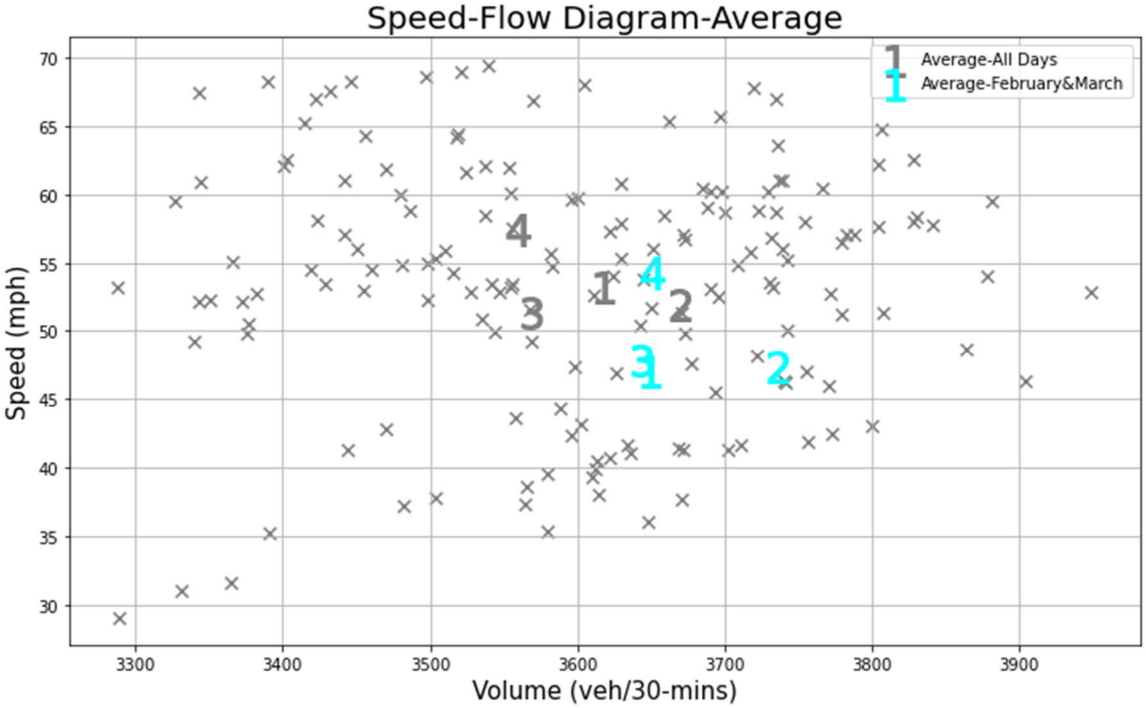


Figure 3-12 Traffic fundamental diagram with highlighted average day data points for Segment 2 for four time slices

Heat Maps

Heat maps based on the key measures, such as volume and travel time, are constructed for Segment 2 out of the three segments in the network. The vertical solid black borders divided the heat maps by clusters, resulting from clustering with the spatiotemporal segregated data, as shown in Figure 3-13 and Figure 3-14. The horizontal lines divide the heat map by the four investigated time slices. On the x-axis, each column corresponds to a day within a cluster, with the last two columns representing the average value of all days and the average value of the days in the peak months (February and March), respectively. The representative day of each cluster is displayed in both figures with a red box surrounding it.

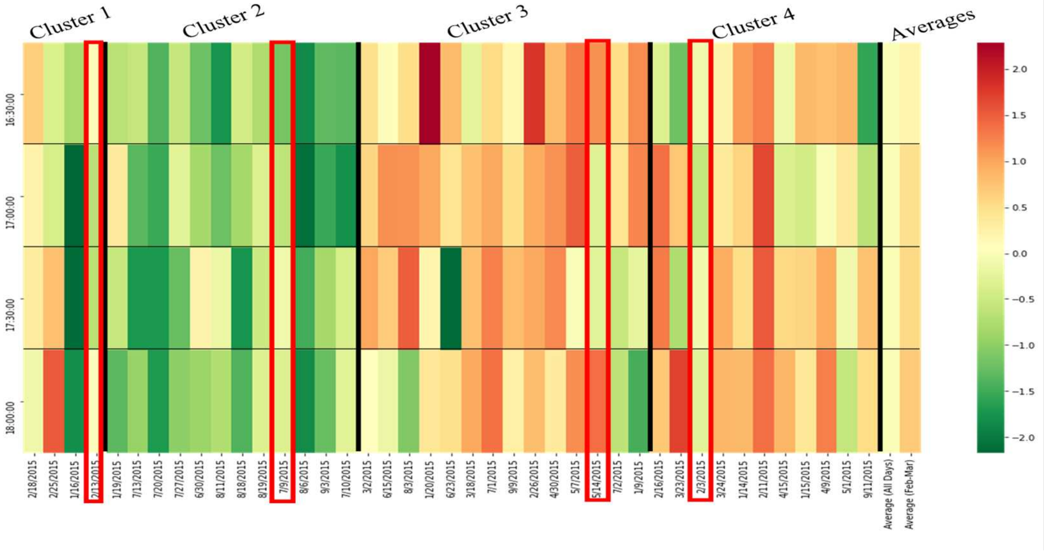


Figure 3-13 Heat map of Segment 2 displaying traffic volume

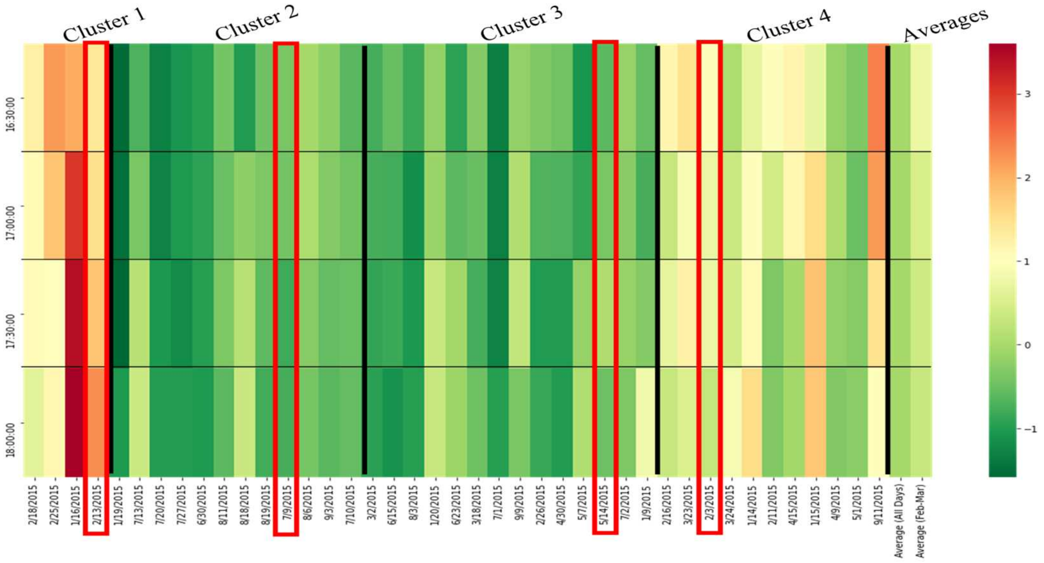


Figure 3-14 Heat map of Segment 2 displaying travel time

It is evident from the heat maps that Cluster 1 groups together the days with volumes that are lower than capacity and high travel times indicating congested conditions constrained by capacity. Cluster 2 consists of days with the lowest volumes and lowest travel times, whereas Cluster 3 has high volumes and relatively low travel times, indicating conditions that are close to but below the capacity. Finally, Cluster 4 lower volumes but higher travel times compared to Cluster 3, indicating that this cluster represents traffic volumes above the capacity of the segments, but not as bad as the conditions of Cluster 1 since the travel times in Cluster 4 are generally lower than those in Cluster 1.

It is clear from the last two columns in Figure 3-13 and Figure 3-14 that both methods of averaging clearly levels out the variation in volume and travel time, as significantly less variation can be observed with the average days compared to the variations obtained with the resulting clusters. In comparison to the identified clusters, the averages overestimate or underestimate the volumes and travel times. Hence, when analysts choose an average day to represent a certain network condition, different travel patterns are diluted to become a singular travel condition that incorrectly characterizes the network. Clustering that uses spatiotemporal segregation effectively separates the different travel conditions within the network.

Given that there are four identified representative days (one for each resulting cluster) for normal (event-free) days, the next issue to address is which one of these four days should be used in the modeling. Table 3-11 shows the representative day for each cluster and the percentage of days for each of the four clusters resulting from different levels of segregation in time and space. The analyst can examine the number of days in each cluster and the congestion level in the representative day to determine which day(s) to model. As stated earlier in this section, Cluster 1 and Cluster 4 represent the congested conditions on the corridor. Table 3-11 indicates that Cluster 1, which has the highest level of congestion, as indicated earlier, represents 10% of the data points, while Cluster 4 represents 27% of the data points. Depending on the analysis scope, the analyst may decide to model the representative day for Cluster 1, the representative day for Cluster 4, or more than one representative day, if multiscenario analysis is to be modeled.

Table 3-11 Number of days in each resulting clusters

Clustering Method	Cluster Components	Representative Day	Percentage of days
Spatiotemporal	1	2/13/2015	4(10%)
	2	7/9/2015	12(29%)
	3	5/14/2015	14(34%)
	4	2/3/2015	11(27%)
Temporal	1	7/13/2015	8(20%)
	2	4/9/2015	12(29%)
	3	2/25/2015	4(10%)
	4	3/2/2015	17(41%)
Spatial	1	9/9/2015	24 (59%)
	2	7/10/2015	2(5%)
	3	2/13/2015	4(10%)
	4	8/19/2015	11(27%)
No Segregation	1	2/16/2015	19 (46%)
	2	7/20/2015	2(5%)
	3	7/13/2015	16(39%)
	4	2/25/2015	4(10%)

3.12.5 Conclusions

The findings of this study indicate the need for methodological changes, first in how representative days of traffic conditions are obtained and second in how clustering is done. With regard to the selection of representative days methods, selecting a representative day based on averaging the traffic measurements for the whole year or even for the peak months of the year does not produce acceptable measures for traffic analysis and simulation. Such averaging will produce measures for conditions that do not occur in the real world and will also mix the high congested conditions with lower congested conditions resulting in measures that underestimate the congestion of the critical days. With regard to the clustering methodology, this study clearly shows that clustering using measures that are segregated in space and time (referred to as spatiotemporal clustering in this study) produced better representation of the variations in traffic conditions in the year. In addition, the findings of this study allow additional conclusions about the clustering method as described below.

This study answered questions regarding the selection of the best day(s) for traffic analysis and identified methods for this selection using cluster analysis. The study showed that the use of input measures to clustering that are segregated in space (by road segments) and in time (by interval of the peak period) produces better clustering results compared to the use of input measures that are aggregated in time and/or space. The study also compared the quality of the results with using different clustering algorithms and number of clusters. The K-means clustering method with four clusters and spatiotemporal segregation level produced the best clustering results. The study showed that despite its theoretical advantage, the GMM clustering was less effective than the K-means clustering in identifying the traffic patterns in this study.

The results presented in this study also clearly show that the use of an average day of the year or an average day of the peak season is not a good approach for selecting a day for the analysis. In addition to the fact that averaging volume and travel time data results in synthetic days that do not occur in the real world, such averaging results in diluted congestion levels. The analysis of the case study in this research indicates that a large percentage of the days (the days in Clusters 1 and 4, which constitute about a third of the days) have significantly higher congestion levels than the congestion level of the average days. Thus, the use of the average day for making highway design decisions for example can result in the under-design of the facility.

In assessing the results of the results of clustering, this study clearly shows the need for the use of techniques based on traffic engineering concepts of the type recommended in this study, in addition to the standard statistical measures of clustering quality. It is recommended to evaluate the clustering and representative day identification results using a combination of statistical techniques such as the t-SNE plot and techniques from traffic engineering literature such Sum of Representative Day Distances, heat map and fundamental traffic diagram.

CHAPTER 4: ASSESSMENT OF AVAILABLE SIMULATION PLATFORMS

4.1 INTRODUCTION

This chapter reports on the results of Task 3 of the project that evaluated traffic analysis platforms that could potentially meet FDOT needs. The task identified a set of capabilities and used these capabilities to compare the analysis tools.

Chapter 2 of this report presented the findings from Task 1 of this project that involved conducting a Web-based survey of modelers from around the State of Florida in addition to interviews with eight major stakeholders that are expected to be impacted by enhancing simulation practices in Florida. The goal is to identify the applications of simulation modeling and the needs of simulation modeling in Florida. Based on 61 public and private sector responses to the survey and the discussions in the interviews, most modelers in Florida use analytical (sometimes referred to as deterministic) analysis procedures and tools like the HCM-based analyses and Synchro analyses, in addition to the use of simulation modeling in some cases. In general, the selection of the tools to use is made by the agency based on conditions such as closely spaced intersections, high demand-to-capacity ratios in urban areas, backups between intersections and/or interchanges, complex system configuration, express lane use, and so on. All of these factors are examined in combination with the survey responses. In some cases, when using simulation, HCM analysis is performed for initial screening of the alternatives, and simulation is used later for a more detailed analysis. When a more detailed analysis of the operations of multiple intersections is needed than those of the HCM and Synchro analysis, analysts use SimTraffic, which is a microscopic simulation tool that can be available from the same user interface as the Synchro tool, specifically for small projects where such use is determined to be adequate in lieu of the using a more detailed analysis through the use of software like Vissim or TransModeler. When selecting the tool and analysis type, the ease of use, available expertise, and comfort level with the tool were mentioned as criteria in the responses to the survey mentioned above. There was a concern among some respondents to the survey that some tools like Vissim and TransModeler require a lot of effort but provide limited additional benefits. There is a need to justify the extra time and expense required for simulation.

The remaining sections of this document include a comparison between the analysis capabilities of a number of deterministic tools and simulation tools. The compared deterministic tools are the Highway Capacity Software (HCS) and Synchro. The compared simulation tools are Vissim, TransModeler, and SimTraffic. It should be noted that SimTraffic is not a standalone software; the user needs to provide the input to the tool using the Synchro user interface. The CORSIM simulation tool was not included in the comparison due to the decreasing use of this tool by simulation modelers in the state of Florida and the Nation, as well as limited user support provided for the tool. It should be noted that the comparison presented in this document does not include comparing the multiresolution and dynamic traffic assignment capabilities. Among the compared tools in this study, only Vissim and TransModeler have these capabilities.

The comparison among the traffic analysis tools in this document utilized the official manuals, user guides, and other documents. The main utilized documents are the Synchro Studio 11 User

Guide (Cubic ITS Inc., 2019), PTV Vissim 2021 User Manual (PTV AG, 2021), Vissim's RBC User Manual (PTV AG, 2020), HCS Users Guide (McTrans, 2019), North Carolina Department of Transportation (NCDOT) guidelines for TransModeler (NCDOT, 2016), and TransModeler Program Help documents. However, the study also evaluated utilizing model runs the tool's consideration of selected features including lane width, grade, and truck presence.

4.2 GENERAL COMPARISON

This section presents a comparison of the general capabilities of the compared tools. These compared general capabilities include modeled facility types, analysis period, demand representation, modeling oversaturated conditions, truck specifications, transit modeling, non-motorized traffic modeling, speed specification, car-following behaviors, impacts of lane changing, and capability of modeling advanced strategies and technologies.

4.2.1 Modeled Facilities

An important aspect of the selection of the tool is the ability to analyze urban streets, freeways, rural highways, or combinations ranging from single intersections and single freeway segments to linear facilities and grid networks. The HCM/HCS has a number of procedures for individual intersections and freeway segments of different types. This includes basic, merging, diverging and weaving freeway segments, and signalized, stop sign, and roundup facilities. In addition, it is capable of modeling linear freeway and arterial facilities. However, the current version of the procedures of the HCM (HCM6 or HCM 2016) is not able to model grid networks and the interaction between freeways and arterials. The interaction between individual facilities cannot be accounted for by HCM procedures. The HCM (and the assessed HCS tool that implements the HCM procedures) is also capable of analyzing two-lane and multi-lane rural highways.

Synchro and SimTraffic can only analyze urban arterials. The current version of Synchro is also capable of analyzing grid networks. Although the Synchro/ SimTraffic claims that it is capable of modeling freeway merging segments and its interaction with signalized arterials, it should be recognized that in reality, SimTraffic is an arterial simulation model, and its ability to accurately model freeway segments is questionable and should be avoided.

Commercially available simulation tools like Vissim and TransModeler are able to analyze all types of freeway and urban street facilities and network configuration. TransModeler can also simulate passing on two-lane rural highways based on choice models developed using laboratory experiments that were slightly augmented and adapted for the simulation context in TransModeler. Traditionally, analysis tools place a limit on the number of vehicles and network size that can be modeled (number of nodes, number of links, number of lanes per link, and number of sign- or signal-controlled intersections). With the advancement in computing power and software, the size of the network that can be modeled has increased significantly. Table 4-1 shows the limits of the Vissim, TransModeler, HCS Freeway, HCS Street and Synchro/SimTraffic.

Table 4-1. Limits of simulation tools for vehicle and network size

Features	Vissim	TransModeler	HCS Freeway	HCS Street	Synchro / SimTraffic
Vehicle Number	Unlimited (Vissim stopped working at 99,999,999 vph)	999,999,999 vph	99,999 vph	99,999 vph	20,000 vph per movement
Number of Nodes	Unlimited	Not available	-	Not available	Not available
Network Size	26,098 mi × 26,098 mi	Not available	-	Not available	67,000,000 ft ≈12,689.4 mile
Length of Links	26,098 mi	Not available	99,999 ft	99,999 ft	60,475,903 ft ≈11,453.77 mile
Number of Links	Unlimited	Not available	Unlimited	Max 4 links/ approaches	Unlimited, but max 8 approaches / links per intersection
Number of lanes per link	100	Not available	9	9	Maximum 8 through lane. For intersection, 8 UT, 8 LT and 8 RT possible.
Number of Signal Controlled Intersections	999,999	Not available	-	Not available	Not available
Analysis Period	999,999,999 seconds	31 days	Unlimited 15-min interval	Unlimited 0.05-3.0 h interval	120 minutes
Pedestrian Input	100,000	2,147,483,647	-	5000	3,000

Finding: The HCM/HCS procedures can be used to analyze local intersections and segments, in addition to linear freeway and arterial segments. In addition, Synchro and SimTraffic documentation stated that these tools can model grid street networks. Synchro and SimTraffic cannot model freeway segments. The HCM/HCS has procedures to model rural two-lane and four-lane highways. The HCM/HCS, Synchro, and SimTraffic cannot model an integrated network of freeways and arterial streets. A main advantage of Vissim and TransModeler is their ability to model a network of model freeways and arterials and their interactions. TransModeler can also model two-way two-lane rural highways.

4.2.2 Analysis Period

The ability to specify time-variant conditions is important to model the growth and dissipation of the congestion and queues from one period to the next considering the variations in traffic during the peak period. Generally, the local intersection segment procedure models one period with a default duration of 15 minutes. However, the Freeway Facility procedure of the HCS allows analyzing multiple 15-minute periods during the peak with varying demands. The arterial street facility procedure of HCS allows for the analysis of multiple periods with an interval from 0.05 to 3 hours, with a default of 15 minutes.

Synchro and SimTraffic can model the traffic in multiple periods. The user can set the analysis period from 5 minutes to 180 minutes in Synchro, and 1 minute to 120 minutes in SimTraffic. When setting the multi-period analysis, the analysis period in Vissim can be set from 1 second to 999,999 seconds, and TransModeler from 1 second to 31 days. All investigated microscopic simulation models allow for the specification of a warm-up or seeding time (SimTraffic) to fill the network with traffic.

Finding: Traditionally, the HCM/HCS procedures for isolated intersections and segments were developed to analyze the peak 15 minutes within the peak period. However, the freeway and arterial facility procedures developed later allow modeling multiple periods, although the length of the period is still generally fixed at 15 minutes. Synchro, SimTraffic, TransModeler and Vissim are flexible in simulating multi-periods with varying lengths.

4.2.3 Demand Representation

The users of Synchro, SimTraffic and the HCS are required to specify the 15-minute traffic flow rate (in vph) or percentage of the total approaching traffic for each turn movement at intersections and merge/diverge areas. The users of Synchro and SimTraffic can specify a sink volume and a source volume for each link, but not the exact the locations of the points of entries at the midblock. SimTraffic also assumes sink and source volumes if the flow is not balanced. The users of SimTraffic can also specify the "local pairing" of volumes between a pair of upstream and downstream intersections (for example, the percentage of the northbound left at the upstream intersection that makes a right downstream). If the user does not specify a local pairing of volumes, which is common, the tool assumed the pairing based on the turn movement proportions at the downstream intersections. Other than this, SimTraffic does not have knowledge of the origins and destinations of the vehicles.

Vissim provides four different methods of demand specifications: turn movement volumes, static routes, partial routes, and dynamic traffic assignment. Vissim also allows the specification of public transportation (PT) routes, managed lane routes, and parking lot routes. Static routing defines the paths of vehicles from each origin to all destinations and is widely used in Vissim to define demands. Partial routing is used to distribute vehicles locally and can serve as a part of one or multiple static routes. Once a vehicle comes to a partial routing segment, it follows the credentials of that partial route, and after leaving that segment, the vehicle follows the original static routing decisions. The parking lot route determines a routing decision point to create routes automatically heading to and from a parking lot. The managed lane route defines two parallel routing decisions from the origin section of the managed lane to the destination section. Vissim also allows for the determination of routes between origins and destinations using dynamic traffic assignment. Finally, a condition or strategy can be defined for activating dynamic routing decision, where vehicles will ignore all other routing decisions and follow that strategy. For example, a strategy can be "if a destination parking lot is full, then vehicles will perform a new parking lot selection."

TransModeler allows for the input of turning movement flows or the use of dynamic traffic assignment based on a specified trip matrix. When turning movement volumes are used to specify demands, TransModeler synthesizes vehicle trips from the input turning volumes and assigns the volumes to the network to reproduce demands for any set of dynamic turning movement counts within a few vehicles. However, network coding errors and excessive congestion can prevent the assigned demand from reaching the intersection to produce the traffic flow.

Finding: The HCM/HCS, Synchro, and SimTraffic require inputting the turning movement volumes or percentages of the approach volume at each intersection and ramp. The users of Synchro and SimTraffic can also specify "local pairing" of volumes between a pair of upstream and downstream intersections. An advantage of Vissim and TransModeler is the ability to model the traffic from their origins to their destinations, although both allow the inputting of turning movement counts if the user prefers. Both Vissim and TransModeler allow dynamic traffic assignment. Vissim allows several other advanced routing methods to be used to ensure better replication of the routes from origins and destinations if the dynamic traffic assignment option in the tool is not used. These routes can be identified based on higher level assignment models such as those incorporated in Vissim.

4.2.4 Truck Specification

Chapter 3 of the Highway Capacity Manual (HCM) includes statistics of the attributes of heavy vehicle traffic, including the average weight, length, and power, along with the percentage of trucks of each vehicle class according to the Federal Highway Administration (FHWA) classification, based on data collected in Florida. According to the data, heavy vehicle fleets are mostly composed of FHWA vehicle classes 5, 6, 8, and 9, which represent around 95% of the heavy vehicles. The remaining 5% is composed of FHWA vehicle classes 7, 10, 11, 12, and 13. However, these percentages can be significantly different depending on local conditions, particularly at locations such as at the vicinity of the ports and warehouses.

The impacts of trucks on capacity and traffic operations are considered in all of the tools. However, the detail of this consideration varies. The HCS freeway procedures allow for the specification of the proportion of two types of trucks: the single unit truck (SUT) according to FHWA classification from 5 to 7, and tractor trailers according to FHWA classification 8-13. The HCM procedures consider the impacts of the lengths and acceleration/deceleration characteristics of a typical truck in each of these two categories. The length of the truck has an impact on the space of roadway occupied by a truck compared to the space occupied by a passenger car. The acceleration and deceleration properties of a truck affect the safe vehicle following distance, maximum sustainable uphill speed (crawl speed), and maximum safe downhill speed of trucks. A higher weight-to-power ratio results in the lower acceleration rate and lower crawl speed. Exhibit 3-16 shows that the weight to power ratio (lb/hp) for a single unit truck (SUT) is 48-135 lb/hp, and for a tractor trailer (TT), 77-181 lb/hp for trucks on a freeway. Also, the average length of SUT is 28 to 30 feet, and for TT, 59 to 95 feet. The signalized intersection procedure in the HCM/HCS and Synchro can assess the impacts of heavy vehicles on capacity specification by allowing the user to specify the proportion of one type of truck, which is assumed to represent a typical truck. SimTraffic allows for the specification of four types of trucks, two types of passenger cars, and one type of bus. The user can vary the proportion, acceleration/deceleration, and dimensions of these types of vehicles.

In TransModeler, the user can input the percentages of several types of vehicles, including single unit truck, trailer truck, and pickup. The user can specify the mean, standard deviation, and distribution of the mass and power parameters for each vehicle class. Vissim allows for the specification of the distribution of the length, weight, power, and acceleration/deceleration characteristics of vehicle classes with no limitations on the number of heavy vehicle types.

Finding: Synchro and the HCM/HCS applies factors to reduce the saturation flow rates and capacities based on the proportion of the trucks in the traffic stream. However, these factors assume one type of truck with specific power to weight ratio for arterial analysis and two types of trucks with specific power to weight ratios for the HCM freeway analysis. SimTraffic can model four types of trucks. The user can vary the proportion, acceleration, and dimensions of these vehicles for use in Synchro. TransModeler can model three types of trucks: single unit truck, trailer truck, and the user can specify the mean, standard deviation, and distribution of the mass and power parameters for each vehicle class. Vissim can specify the distribution of the length, weight, power, and acceleration/deceleration characteristics of vehicle classes, including heavy vehicles with no limitations on the number of the truck types in the program. If the trucks are expected to have significant impacts on system performance, the user needs to identify the truck type mix in the traffic stream, determine if the analysis tool allows inputting this mix, and then at least examine if the impact on the performance of the truck mix based on simulation results is logical.

4.2.5 Transit Modeling

The HCM/HCS signalized intersection procedure calculates the impact of bus operations on the saturation flow rates based on the input values of the bus stopping rates per hour within 250 ft upstream or downstream of the intersection stop line that block the flow. Synchro also implements a similar calculation to estimate the impacts on saturation flow rates. Synchro and SimTraffic consider the impact of bus stops on capacity based on equations but do not implicitly model transit vehicles.

The number of bus blockages are also used to calculate an impact on the time headway and thus capacity. However, bus stops are not explicitly modeled in SimTraffic, and therefore, the tool is not ideal for analysis that requires a special consideration of public transit.

Vissim has a detailed public transit model that can provide a detailed simulation of bus stops and interaction with the traffic. Vissim is flexible in allowing for the specification buses, light rail, and commuter rail operations with various characteristics and operation performance. Vissim can model bus routes, schedules, and stops and the interaction of public transit with general traffic. The user can specify alighting time, boarding time, and bus capacity. The tool can also calculate the alighting and boarding times based on the passengers at each bus station.

TransModeler can model transit vehicle classes, including buses, trains, and articulated buses. The user can input transit vehicle parameters, including the vehicle class, seating capacity, total capacity, dead time, alighting time, boarding time, and crowding factor. TransModeler modeling of the transit systems considers transit routes, including bus lanes and wayside stops; a route system that defines one or more routes making up the entire transit system, including routes and stops; a definition of transit vehicle types, including attributes of the vehicle that influence dwell times at stops; and a transit schedule (optional) containing the scheduled arrival times for one or more stops on each route and for one or more trips serving each route.

Finding: Synchro/SimTraffic and the HCM/HCS consider the impacts of upstream bus stops in the close proximity of the intersection on the saturation flow rate. However, they do not explicitly model bus operations and the detailed interaction of individual buses with the traffic. Vissim and TransModeler allow for the modeling of different types of buses and trains, including routes, bus stops, and dwell times at bus stops. These simulation tools can estimate the performance of public transit routes.

4.2.6 Non-Motorized Traffic Simulation

The HCM/HCS and Synchro consider the impacts of pedestrian and bicycle flow rates, focusing on the impacts of those pedestrians that are in conflict with the conflicting turning right vehicles. Specifying non-zero pedestrians per hour decreases the saturation flow rate for the conflicting turn movements. The pedestrian crossing demands in the HCM/HCS and Synchro also affect the green split in signal time if pedestrian phases and push buttons are provided. The Walk plus Clearance Interval time is used in combination with the probability of a pedestrian phase call to estimate the green splits. Synchro has the option to code pedestrian crossing demands and a crosswalk with a raised median for two-stage crossing. Synchro has two options to input pedestrian crossing volume: pedestrian calls and conflicting pedestrian.

SimTraffic can simulate pedestrians by defining the conflicting pedestrians in the volume setting and pedestrian calls in the phase setting in Synchro. The number of conflicting pedestrians is used in SimTraffic to estimate the number of pedestrians crossing the roadway to estimate the signal timing allocated to pedestrians. However, the SimTraffic output does not show any pedestrian-related performance measures like pedestrian delay or speed or travel time.

Vissim can model in detail the pedestrian, bicycle, and motorcycle traffic. Crosswalk operations can also be modeled, including two-stage crossing in Vissim, which considers the impact of crosswalks. In addition, for a more detailed analysis, Vissim has an add-on named PTV VisWalk to analyze pedestrian traffic. With this tool, the users can define the origin and destination of pedestrians and necessary walkways. The outputs of the VisWalk include a pedestrian's walking speed, walking delay, walking travel time, and volume. VisWalk uses what is referred to as the Social Force to define the walking behaviors for pedestrians in the simulation. The PTV VisWalk is only suitable to simulate pedestrian and other non-motorized modes like bicycles or wheelchair users. However, VisWalk and Vissim can be combined to model the interaction between pedestrian with motorized traffic.

TransModeler simulates pedestrians on crosswalks to capture the effect of pedestrians on traffic flow in signalized intersections and can also simulate bicycle and motorcycle traffic. TransModeler uses pedestrian crosswalks to model the effect on the traffic flow of pedestrians crossing a street.

A pedestrian crosswalk is represented by one or two walk segments, one for each side of the street, depending on whether the street is one-way or two-way.

Finding: The user can specify non-motorized traffic in HCM/HCS and Synchro/SimTraffic to be used in estimating the impacts of the conflicts with the turning vehicles on the saturation flow rates of the turning movements and to estimate the changes in the actuated signal timing due to pedestrian phase activation. However, non-motorized traffic, including individual pedestrians or bicycles, are not explicitly modeled to be able to determine the stochasticity of their operations and to derive the performance measures associated with these operations, as can be done with Vissim and VisWalk. Although TransModeler can model the effect of pedestrian on vehicular traffic capacity, it does not produce pedestrian's performance measures.

4.2.7 Car-Following Behavior

Car-following models are an important component of microscopic simulation. SimTraffic has two car-following models, fast-following and slow-following. The fast-following model is utilized by a following vehicle when the speed of the leading vehicle is more than 2 ft/sec (0.6 m/s). The slow-following model is employed in the case of a stopped or slow-leading vehicle, like when a vehicle is stopped at a mandatory lane change point. SimTraffic first calculates the distance between the moving vehicles or between a vehicles to a stopping point. Then, the fast-following model estimates a safety factor (DSafe) based on the distance between vehicles (DBv), speed of the leading and following vehicles, and desired headway. Based on the value of the safety factor, the following vehicle will decide to either accelerate or decelerate. The recommended acceleration or deceleration for the slow-following model is estimated based on the distance between vehicles (DBv) and minimum acceleration/deceleration defined for vehicles. This traffic-following model is a basic model compared to the more advanced car-following models used in advanced tools, and it is not clear if the model has been selected based on previous research and/or verified in the field.

Vissim uses the Modified Wiedemann car-following model, which is a psychophysical model that uses thresholds or action-points where the driver changes his/her driving behavior. The drivers react to changes in spacing or relative speed to the leading vehicle only when these thresholds are crossed. Three models are available in Vissim: The Wiedemann 74 model suitable for urban traffic, the Wiedemann 99 model which is suitable for freeway traffic, and no Interaction (vehicles do not respond to other vehicles, which can be used for a simplified pedestrian behavior, although pedestrian-specific models can be used).

TransModeler has vast option of changing driving behavior compared to Vissim or Synchro. Users can modify driving behavior for car-following, lane changing, passing, merging, yielding and roundabout. For CFM, the user can select the GM model, Gipps model, Wiedemann models, Intelligent Driver model, and a combination of different models. Similarly, for LC, the user can use several models.

Finding: Vissim implements the Wiedemann car-following model, which is a recognized car-following model. TransModeler allows using the GM model, Gipps model, Wiedemann models, and Intelligent Driver model, which is a nice research capability. The vendor can provide guidance as to when these models should be used in practice.

4.2.8 Impact of Lane Changing

Lane changing ahead of the intersection can have an impact on the operation. SimTraffic has two specific driving behavior parameters that can be fine-tuned: the average lane changing time (seconds) and the percentage of lane changing variance (%). The average time denotes the mean time required to perform a lane change maneuver by the vehicles, and the variance (%) denotes the variance of the lane changing time among the drivers for a specific driver type. Per the Synchro/SimTraffic Manual, fine-tuning these two parameters would increase or decrease congestion levels. The users can modify the average lane changing time and percentage of lane changing variance parameters of the driving behaviors of the provided ten driver types to mimic real world conditions. In SimTraffic, the lane changing behavior can be impacted by specifying a mandatory distance, which refers to the distance between the stop line and the point where a lane change must start. If a vehicle is unable to initiate lane changing before this point, then the vehicle will stop and wait until it starts lane changing. In that case, the surrounding vehicles from the next lane will cooperate with the subject vehicle and allow it to merge. The mandatory distance is regulated by a mandatory distance adjustment factor, which ranges from 50% to 200% for the ten different driver types. The positioning distance refers to the distance from the mandatory point to the point where a vehicle first tries to perform lane changing. Before this point, vehicles are uninformed about the upcoming lane change requirements. Like mandatory distance, the positioning distance is also controlled by a factor, which is called a positioning distance adjustment factor, which ranges from 50-200% based on driver types. SimTraffic seems to only consider mandatory lane changing and uses a simplified car-following model.

TransModeler allows for the fine-tuning of several lane changing model parameters. Three potential steps are followed in TransModeler to model lane changing. As with Vissim, TransModeler has the Mandatory Lane Change (MLC) and Discretionary Lane Change (DLC) models. For MLC, when looking ahead, the model considers lane drops, in addition to turns or exits. For instance, if a lane connector's connectivity bias α is less than 1, some fraction of drivers (1 - α) will make every attempt to make a mandatory lane change out of the lane before it ends. The connectivity bias can be used to model a variety of conditions, such as a lane drop, where use of a lane is undesirable, or use of other lanes is more desirable. When a vehicle "looks ahead", it will make note of any points along its path within the look-ahead range where a diversion (i.e., a turning movement, off-ramp exit, or other fork in the road) is necessary. All lane changing decisions made within a critical distance upstream of these critical points will be mandatory. The critical distance may also be a function of the type of roadway facility on which the vehicle is traveling. For instance, on higher speed facilities such as freeways, the critical distance may be longer. Conversely, on lower speed facilities, such as urban streets, the critical distance will typically be shorter because decisions can be made, and actions can be taken over shorter distances. The DLC is used to achieve a perceived improvement in driving. The following are some of the variables in TransModeler that impact the discretionary lane changing decision: path influence factor, heavy vehicle ahead, on-ramp ahead, transit vehicle ahead, parking and standing, and so on. TransModeler allows for the use of one of three gap acceptance models for lane changing: Linear Gap Acceptance, Non-Linear Gap Acceptance, and NGSIM Gap Acceptance.

Vissim has a detailed rule-based MLC and DLC lane change model that can be fine-tuned to replicate observed or expected performance, including lane change distance, emergency stop distance, and various drivers' lane change aggressiveness behaviors. In Vissim, the user can fine-tune the lane changing parameters, which are available as link (connector) parameters and others as driving behavior parameters. The connector parameters include the desired direction, emergency stop distance, lane change distance, exception for vehicle class, lane change rule, necessary lane change (route), diffusion time, minimum clearance, maximum deceleration for cooperative braking, advanced merging, vehicle routing decisions look ahead, and cooperative lane change.

Finding: The HCM/HCS and Synchro as macroscopic tools do not explicitly model lane changing, although the HCM implicitly considers the impacts of lane changing in their merge, diverge, and weaving freeway segments. Both Vissim and TransModeler have detailed mandatory lane change (MLC) and discretionary lane change (DLC) with multiple parameters that can be fine-tuned. SimTraffic allows only MLC (no DLC), and the lane changing model is simplified with only two parameters.

4.2.9 Effect of Oversaturation

Traditionally, the HCM and Synchro have not dealt with oversaturated conditions or queues that spillback to upstream intersections. However, the procedure for the calculation of delays at signalized intersections add a term to the calculation equation in an attempt to account for oversaturated conditions.

The HCM freeway and arterial procedures introduced in the 2010 version of the HCM can partially deal with queuing as it models the queue growth from one interval to the next. The facility procedures require that the queues do not extend beyond the spatial and temporal boundaries of the modeled system. The HCM/HCS allows the user to input the link storage length and turn bay length to model the queue spillover or spillback in the facility's procedures. The Synchro's percentile delay method includes an additional delay component related to spillback from adjacent intersections. This delay includes the analysis of spillback, starvation, and storage blocking. For spillback analysis, the upstream capacity is set to zero whenever the queue extends to the upstream link.

SimTraffic, Vissim, and TransModeler as microscopic simulation models consider the impact of link spillback and turn bay spillover. SimTraffic, Vissim, and TransModeler have the ability to model the queue growth from one interval to the next. They can also model oversaturation and spillover from the turn bays to adjacent lanes and from one segment to the next. Additional advantages of simulation models are their ability to consider the impact interactions of upstream and downstream bottlenecks, and downstream hidden bottlenecks that can appear after solving the upstream bottlenecks. The initial queue can be accounted for by using a warm-up period.

Finding: Although the HCM/HCS and Synchro procedures can consider the impact of congestion and spillbacks, the operations under oversaturated conditions and the spatial and temporal influences of congestion are modeled using microscopic simulation models. These models have the ability to model the queue growth from one interval to the next. They can also model oversaturation and spillover from the turn bays to adjacent lanes, and from one segment to the next. Additional advantages of simulation models are their ability to consider the impact interactions of upstream and downstream bottlenecks, and downstream hidden bottlenecks that can appear after solving the upstream bottlenecks.

4.2.10 Posted Speed Limit/Approach Speed

The posted speed limit/approach speed and any consideration of the acceleration and deceleration in the HCS/HCM procedure and Synchro are deterministic and at the macroscopic level. There is no consideration of the variations of these parameters by driver and vehicle types.

Vissim allows for the input of desired speed distribution for each vehicle type. If a vehicle is not hindered by other objects, it will travel at the desired speed. The distributions of the desired acceleration, maximum acceleration, desired deceleration, and maximum deceleration of vehicles can also be specified. By default, Vissim has four motorized vehicle types (Car, HGV, Bus and Tram) with four desired acceleration and deceleration functions, respectively. In addition, there are four non-motorized vehicle types (Man, Woman, Bike Man and Bike Woman) with two sets of acceleration-deceleration functions (Pedestrian and Bike) for these non-motorized vehicle types. Time-variant speed zones can be specified for each link and turn movement.

In TransModeler, the desired speed distributions can be modified by roadway type like freeway, major arterial or minor arterial. These speed distributions can be further modified by vehicle and driver type. In addition, time variant speed limits on individual links can be specified. When vehicles approach a speed limit sign, they adjust their desired speeds according to the speed limit compliance distributions defined in the model parameters. Drivers will maintain that desired speed until they encounter a new speed limit, either by passing another speed limit sign or by entering a link with a different road class, and thus a different default speed limit. TransModeler allows for the modification of both the maximum and normal acceleration to account for the variability among driver behaviors and the age and quality of a vehicle's brakes.

In SimTraffic, the user can input speed factor and deceleration for different driver types. These factors are multiplied by the link speed coded in Synchro to estimate the maximum speed of each vehicle. The default ranges of the speed factors are 0.85 to 1.1. The user can input a maximum of ten driver types.

Finding: Synchro and HCM/HCS procedures use average desired speeds for a link and do not consider in detail the variations in individual vehicle speeds on performance, although the HCM arterial street facility procedure has a platoon dispersion algorithm that considers the change in the platoons as they progress from upstream to downstream signals. TransModeler, Vissim, and SimTraffic allow for the changing of speed by link and vehicle/driver types. In TransModeler, users can input speed limits for 21 road classes (freeway, rural highway, expressway, weaving, system ramp, collector-distributor, ramp, minor arterial, major arterial, minor collector, major collector, local street, access road, trail road, roundabout, tunnel, rail, waterway, freeway-piecewise linear and freeway-Van Aerde), each of which may follow six desired speed distributions (standard, school zone, work zone, freeway, major and minor arterial). TransModeler and Vissim have more flexibility in assigning speeds to more vehicle/driver types. In addition, it seems that SimTraffic does not consider the stochasticity of speed for each vehicle type.

4.2.11 Modeling of Advanced Strategies and Technologies

Modeling of advanced strategies and technologies requires a powerful application programming interface (API) facility in the simulation tool. Increasingly, software-in-the-loop (SIL), hardware-in-the-loop (HIL), human–in-the-loop (HuIL), and vehicle-in-the-loop (VIL) simulations have been used to simulate the applications of emerging technologies and advanced features. These features can collectively be referred to as X-in-the-loop (XIL).

Although the HCM has a high-level procedure that can be used to analyze the impacts of active traffic and demand management (ATDM), such strategies are best evaluated using microscopic simulation models; particularly when the analysis is conducted to support operational decisions. Mesoscopic models, combined with microscopic simulation, can also be used to examine the impacts of strategies and technologies on strategic behaviors such as route diversion due to the advanced strategies. These simulation tools are sensitive to dynamic changes in the system due to strategies such as traffic-responsive and adaptive signal control, ramp metering, managed lanes/ congestion pricing, bus rapid transit, traveler information, and incident management.

New materials are being added to the HCM to address the impact of specific connected automated vehicle (CAV) features, including cooperative adaptive cruise control, platooning, and dynamic merge control on capacity. These can help in accounting for the increased market penetration of these specific features on the capacity of individual segments. However, simulation modeling is needed to assess the network-wide impacts. In addition, there are many other connected, automated, and cooperative vehicle automation features that impact the safety and mobility of the transportation system. Simulation modeling can be used for analyzing the impacts of all features, in addition to assessing the system-wide impacts beyond the local impacts of the emerging technologies. Built-in features have been introduced into models like Vissim and TransModeler to simulate CAVs. In addition, the user can develop extensions of these models using the API facilities provided with these tools. Further discussion of CAV modeling is presented in a separate section later in this document.

The TransModeler API is designed to support a variety of contemporary programming languages, including C/C++, VB and C# supported in .NET. The API provides a set of Component Object Model- (COM) based interfaces. These interfaces use an object-oriented approach and hierarchical structure to represent the data models upon which a TransModeler plugin can be built. TransModeler supports ACDSS (adaptive control decision support system) as software-in-the-loop. However, it currently does not have the facilities to support the user in developing XIL applications.

Vissim provides C style Signal API, out-process COM API, event-based COM scripting and VAP for coding and customizing network. Moreover, Vissim uses pattern-based APIs, such as- ASC3, which is based on Vissim C-style signal API using TCP to communicate with the ASC virtual controller software, phase-based APIs, and NEMA emulator APIs. Vissim supports several built-in software-in-the-loop, including balance adaptive signal control, Econolite ASC/3 Virtual Controller, and McCain controllers. In addition, Vissim is very flexible in allowing the user to build various XIL applications.

SimTraffic has a feature called Controller Interface (CI), which interacts with a CI device connected to a controller to simulate the operation of the controller with simulated traffic. Trafficware, the parent company of Synchro, has a central traffic management software named ATMS. Synchro has been integrated with the ATMS software. [1]

Finding: Advanced operations, active management, demand management, and pricing strategies are best analyzed using advanced simulation tools like Vissim and TransModeler. These programs have API facilities that allow for the integration of codes to emulate these strategies with the simulation models. Vissim has the ability to have co-simulation involving software-in-the-loop, hardware-in-the-loop (e.g., signal controller in the loop), human-in-the-loop, and/or vehicle-in-the-loop (including human driven and connected and automated vehicles). TransModeler may have at least some of these capabilities, but this has to be investigated. SimTraffic allows interfaces with controller-in-the-loop but does not allow for the modeling of advanced strategies or additional co-simulation options.

4.3 SIGNALIZED INTERSECTIONS AND FACILITIES

This section compares the capabilities of different tools in modeling signalized intersection and urban arterial segments with signalized intersections.

4.3.1 Lane Configuration

The HCM/HCS can analyze a maximum of four legs and a maximum of 3 lane groups per approach (e.g., left, though, and right). Synchro allows the analysis of any intersection configuration (i.e., 3-leg, 4-leg, and more leg intersections with a maximum of ten lanes per approach). The HCS and Synchro allows for the input of the average lane width for each movement group, but not by lane. The average lane width impacts the capacity of the movement and thus the delay measures. SimTraffic does not have a separate option to input the intersection geometric configuration of the intersection. The same data used as input to Synchro is used as input to SimTraffic. The default lane width in Synchro is 12 feet (3.6 meter), and ranges from 8 ft to 16 ft.

Vissim is flexible in allowing a various number of lanes and lane configurations. However, the lane width does not affect capacity. Thus, the user has to fine-tune model parameters to produce the effect of the widths of the lanes on capacity. TransModeler is also flexible in allowing a various number of lanes, up to 16 lanes in one direction. The default value of lane width used in TransModeler is 12 feet for all lanes. If the lane widths are modeled, there is no effect on operations in TransModeler for lanes coded as greater than 12 feet. Therefore, widths greater than 12 feet

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[1] https://www.trafficware.com/uploads/2/2/2/5/22256874/atms_overview_4.5.pdf

should only be modeled as 12-foot lanes.

In the HCM/HCS procedure, the number of departing lane and lane drop downstream of the intersections are not modeled, and its impact on the capacity of the upstream is not estimated. The HCM suggests that the number of receiving lanes for the left-turn and right-turn movements should be measured separately since the turning cannot be performed properly if an intersection is frequently blocked by double-parked vehicles. HCM recommends determining the number of receiving lanes from field observation.

While the input to Synchro allows for defining the number of receiving lanes, this information is used in SimTraffic, not in Synchro. If the number of the receiving lanes is lower than the entering lanes coded in Synchro, SimTraffic will deliver a warning. Lane drops within a segment cannot be modeled in SimTraffic. However, this may be possible by coding a dummy node at the location of the lane drop.

Vissim and TransModeler are flexible in modeling downstream lane drops. However, the lane merging location and behavior upstream of the lane drop have to be calibrated with consideration of the impact of reducing or increasing the number of receiving lanes in a signalized intersection. Decreasing the number of receiving lanes results in a higher intersection delay and vice versa.

Finding: The HCM/HCS has a limit on the number of approaches and lane groups that can be analyzed (a maximum of four legs and a maximum of three lane groups per approach). Other examined analysis tools do not have this limitation. Lane width impacts capacity in the HCM/HCS, Synchro, and TransModeler. In SimTraffic, the lane width affects the headway factor, which influences the headways and simulation flow rates. The lane width does not affect capacity in the Vissim, and thus this impact has to be approximated by manipulating other input parameters. The impact of the reduction in the lanes on the departing (receiving) approach on vehicular traffic capacity cannot be accurately modeled using analytical/deterministic tools; they can best be modeled using simulation models.

4.3.2 Lane Utilization

The HCM/HCS analysis procedure uses lane utilization for a lane group with more than one exclusive lane. If the lane group has one shared lane or one exclusive lane, then this factor is 1.0. Synchro also calculates the lane utilization based on the factors presented in the HCM equation. However, the users can modify the factor. The used lane utilization factors are shown in Table 4-2.

Table 4-2. The lane utilization factors used in the hcm and synchro

Lane Group Movements	**# of Lanes**	**Lane Utilization Factor**
Thru or shared	1	1.00
Thru or shared	2	0.95
Thru or shared	3	0.91
Thru or shared	4+	0.86
Left	1	1.00
Left	2	0.97
Left	3+	0.94
Right	1	1.00
Right	2	0.88
Right	3	0.76

TransModeler uses the HCM parameters to estimate the lane utilization. In addition, TransModeler can specify a connectivity bias that is used to bias the lane utilization toward or against certain lanes. This is particularly useful in situations where drivers tend to avoid lane(s) in anticipation of merging vehicles or when they have to make a turn. The users can input a connectivity bias between 0 and 1.

In the absence of upstream turns and downstream turn requirements, Vissim randomly assigns traffic to the lanes. If the specified routing involves some of the vehicles turning downstream at a location that is within the lookup distance, the vehicles will attempt to position themselves on the lanes that allow them to make the turns downstream. The lane utilization can also be affected by the lane that the vehicles use to enter the link.

Finding: The imbalance in lane utilization can affect the performance of the signalized intersection. The HCS/HCM and Synchro have default values for lane utilization. Vissim and TransModeler assign the traffic to lanes based on their downstream turns. In addition, TransModeler can use the lane utilization factor from the HCM and input a factor to bias the traffic toward specific lane(s), which is a nice feature to have if it works correctly. It is not clear of how well SimTraffic assigns traffic to lanes. If the user inputs the upstream-downstream demand pairs between upstream and downstream intersections, one may think that the model may be able to assign the vehicles to lanes by considering this pairing. However, this is not certain and needs to be tested.

4.3.3 Approach Grade

The approach grade impacts the capacity calculation in HCM procedure/HCS and Synchro. The HCM/HCS considers the approach grade, which is measured from the stop line to a point 100 ft upstream of the stop line along a line parallel to the direction of travel. Upgrade (above zero) decreases the saturation flow rate/capacity, and downgrade (below zero) increases the saturation flow rate/capacity. The range of the approach grade in HCM/HCS is -6% to +10%. Synchro allows for the inputting of grades in a range from -15% to +15%.

Vissim and TransModeler allow for the inputting of the uphill and downhill slopes of a link in percentages. However, the user needs to calibrate the impact of the grades on capacity.

Finding: Upgrades and downgrades impact capacity in HCM/HCS, Synchro, Vissim, and TransModeler. It is not clear if SimTraffic can simulate the impact of grades. In SimTraffic, the grade or roadway impacts the headway factor, which affects headways and thus saturation flow rates. The impact of the change in capacity with different truck proportions and compositions in different tools should be examined.

4.3.4 Turn Radius and Speed

The HCM/HCS procedures allow for the inputting of the left-turn radius and right-turn radius. The intersections with large turning radii increase the turning speeds and thus capacity. Turn radius affects the left-turn equivalency factor (typically 1.05), and the right-turn equivalency factor (typically 1.18). These equivalency factors affect the saturation flow rate of left-turn movements and right-turn movements. HCS also allows for the input access point for right-turn speed. It affects access point operations, which modify the proportion of arrivals on green for downstream major-street movements. However, HCS does not allow for the inputting of turning speed at signalized intersections. The users can input turn radius and turn speed in Synchro. However, Synchro does not use the turning speed data; only SimTraffic uses the turning speed.

With Vissim, the user can specify turn speeds on the link connectors using desired speed areas to impact the saturation flow headway and thus the capacity of these turns. The turning speed can be controlled by using desired speed area.

In TransModeler, the turn radius can be input by link, and the turn speed can be coded by vehicle fleet type. The user can modify the maximum turn speed for a particular turn type or maneuver by entering the value in the column corresponding to the appropriate turn type or maneuver. TransModeler users can specify specific link-to-link maximum turning speeds in a turn movement table.

Finding: Left- and right-turn radii are used as inputs to HCS/HCM, and Synchro and these values affect the capacities of the associated movements. All three microsimulation models use turn speeds rather than turn radii to impact capacity. TransModeler also allows for the inputting of turn radii. The user should examine how the turning speeds in each of the microscopic simulation tools impact capacity.

4.3.5 Signal Coordination/Arrival on Green

The isolated signalized intersection procedures in the HCS/HCM allows the user to input the arrival type (AT), which is used in the calculation of a platoon ratio for each movement, and the platoon ratio is used in the calculation of the proportion of arrivals on green for each movement. This value is used in the delay calculations. The higher the proportion of platoon arriving during the green, the better the progression and the lower the delay. The HCM/HCS street procedure determines the platoon arrival on green based on the link speed, offset, and distance between the upstream signal timing. The procedure implements a platoon dispersion model to account for platoon dispersion across the link. Synchro determines the platoon arrival on green based on the link speed and the distance between the upstream signal timing. However, it does not implement a platoon dispersion model.

Coordination and offset impacts are modeled in Vissim, TransModeler, and SimTraffic as individual vehicles progress from the upstream signal to the downstream signal. Platoon dispersion can be controlled by the distribution of speed and ability/desire of vehicles to pass each other based on the input calibration parameters. It seems that TransModeler has an option to adjust the HCM AT parameter results based on the simulation outputs, which is an interesting feature.

Finding: The HCM/HCS arterial street procedure applies a macroscopic platoon dispersion model to estimate the arrival on green at the downstream signal based on the link speed, offset, and the distance between the upstream signal timing and the implemented platoon dispersion model. Synchro determines the platoon arrival on green based on the link speed and distance between the upstream signal timing. However, it does not implement a platoon dispersion model. Coordination and offset impacts are modeled in detail in Vissim, TransModeler, and SimTraffic as the individual vehicles progress from the upstream signal to the downstream signal.

4.3.6 Shared Lanes

The HCM/HCS and Synchro have equations for the calculation of the saturation flow rate of shared lanes based on the proportion of turn movement volumes in each lane. When analyzing "shared-plus-exclusive" configurations, the HCM/HCS and Synchro require the user to input the "Percent Turns in Shared Lane" to specify the percentage of left-turn or right-turn vehicles in the shared lanes. Synchro also requires inputting the proportions of the turn movement volumes for shared plus exclusive lane configurations. The HCM/HCS and Synchro use an equivalency factor for the left turn and right turn to calculate capacity based on the turning lane configurations. SimTraffic does not consider the impact of shared lane.

Shared lane can be modeled in Vissim and TransModeler. The resulting capacity of these movements needs to be calibrated. The proportions of the turn movement volumes in the shared lanes are expected to be the result of lane selection and downstream/upstream lane changing and need to be further examined by the users.

Finding: The modeling of shared lanes is challenging. Synchro and SimTraffic have models for estimating the capacities of these lanes but require the user to input the number of vehicles that use the shared lane when there is an adjacent exclusive lane that can be used by the vehicles. Microscopic simulation models assign the vehicles to the shared lanes based on downstream/upstream lane changing. The lane assignment and the resulting capacity estimates need to be further examined by the users. SimTraffic does not seem to consider the impact of a shared lane.

4.3.7 Mid-Block Demands and Constraints

The HCM/HCS and Synchro procedures do not directly account for mid-block parking activity, mid-block significant grade, incidents and work zones, and other mid-block capacity constraints. However, the on-street parking in the vicinity of the signalized intersection can be considered using the HCS procedure. The HCM/HCS procedures allow for the inputting of the number of parking maneuvers that occur directly adjacent to a movement group within 250 feet upstream of the stop line, as measured during the analysis period. A maneuver occurs when a vehicle enters or exits a parking stall, in the range of 0-180 parking per hour. The non-zero parking maneuvers per hour decrease the saturation flow rate for the associated movements.

SimTraffic cannot model midblock constraints. However, it may be able to emulate some of these features with the use of a dummy node, possibly with a dummy signal at the location of the midblock constraints.

TransModeler can simulate on-street parking by using a variety of parameters to control the time it takes to pull into or out of a parking space. Parking parameters are divided into general parking parameters, parallel parking parameters, and angled parking parameters. These parameters impact traffic flow, particularly under congested flow conditions. The length of time it takes to complete a parallel parking maneuver determines to a great extent on the magnitude of that impact.

In Vissim, the mid-block constraints feature can be considered using lane blocking, time variant speed, or using external modules that are coded using the COM facility.

Findings: In situations where midblock constraints and frictions, such as the case with parking activities, work zones, incidents, and parking impact traffic, models like Vissim and TransModeler are recommended. TransModeler has a detailed built-in on-street parking model.

4.3.8 Permissive Left-Turn Modeling

The HCM/HCS has procedures to estimate the capacity of permissive left turns on exclusive lanes and permissive left turns on shared lanes. The capacity for a permissive left turn in an exclusive-lane lane is computed as a function of the number of lanes, saturation flow rate in an exclusive left-turn lane group with permissive operation (vehicle/h/ln), duration of permissive left-turn green time that is not blocked by an opposing vehicle, an adjustment factor for downstream lane blockage, an adjustment factor for sustained spillback, number of sneakers per cycle, and cycle length. The adjustment factor in the HCM/HCS procedure can account for downstream lane blockage using jam density, movement capacity, and number of open lanes when a blockage is present. The adjustment factor for the sustained spillback is computed from the capacity at upstream intersections and the adjustment factor for downstream lane blockage. If the permissive left-turn operation is done from a shared lane group, the capacity is calculated as a function of the effective green time of the permissive left-turn operation (s), the saturation flow rate in the shared lane (vehicle/h/ln), the proportion of left-turning vehicles in the shared lane, adjustment factor for downstream lane blockage, and adjustment factor for sustained spillback and cycle length.

In Synchro, the protected and permitted left-turn maneuvers are also modeled. In SimTraffic, a gap acceptance factor is used to adjust approach gap times that vehicles will accept during protected left turns.

The permissive left turn in Vissim can be simulated using priority rules for the conflicting points between the left-turn traffic and the corresponding opposing through traffic. A driver's gap acceptance behavior can be adjusted in the priority rules using two parameters: minimum headway (feet), and minimum gap time (seconds). The minimum headway is defined as the distance from the start of the potential conflict area at the conflict marker up to the first vehicle moving towards the conflict marker. The minimum gap time is the time in seconds between the first opposing vehicle and the conflict marker. The gap time is usually used to set up the left-turn gap acceptance behavior for the left-turning vehicles, which must yield to the opposing traffic flow.

The user can simulate the permissive left turn in TransModeler using the lane connector tools for the automatic identification of the left turns and opposing movements. TransModeler allows simulation of no left turn, protected only left turn, protected/permitted left turn, and rule-based left-turn operation.

Finding: HCM/HCS and Synchro have detailed permissive left-turn models that can provide good estimates of capacity. The microscopic simulation models allow for better consideration of upstream and downstream intersections, the platooning of opposing traffic that generates different gaps in traffic than random arrivals, the vehicle type (including heavy vehicles), impacts of upstream and downstream congestion, and the stochasticity of drivers' behaviors. It is recommended that when using simulation models to confirm the resulting capacity versus those obtained from the HCM, the difference between basic traffic conditions should be explained.

4.3.9 Right Turn on Red

The HCM/HCS procedures requires that the users input the number of vehicles that turn right at the intersection when the signal indication is red. This is a user input which can be difficult to estimate. This input value is subtracted from the right-turn demand before estimating the delay and level of service of the right turn. Synchro automatically calculates a saturation flow rate for Right Turn on Red (RTOR) and applies this flow rate to a movement when the movement has a red signal. The calculation of the RTOR Saturation Flow Rate is based on the signal timing, the volumes of the subject approach, and the volumes of any merging approaches. It is possible to override the RTOR saturation flow rate to a measured value or hand-calculated value. The RTOR Saturation Flow Rate is sensitive to changes in volumes and timings.

In SimTraffic, right-turn vehicles will make a turning movement on red, if RTOR is allowed. The user can define a gap acceptance factor with a range of 0.85-1.15, which is used to adjust the approach gap time that will be accepted by vehicles for right turn on red.

Right turn on red can be modeled in Vissim using priority rules by placing a stop sign on the right-turn lane. In TransModeler, right-turn-on-red can be modified directly at the state of signals during a given phase by selecting the right-turn-on-red option from a drop-down menu. When right turns on a red signal are permitted in a signal timing plan, right-turning vehicles will come to a stop at the intersection before seeking an acceptable gap in which to turn. If drivers can turn right from more than one lane, it may often be the case that right turns on red are only allowed from the right-most lane. This parameter allows you to control whether drivers can turn right on red from lanes allowing a right turn or only from the right-most lane.

Finding: HCM/HCS requires inputting the RTOR capacity, which is difficult to estimate. Synchro has a macroscopic model that can provide estimates of RTOR capacity. The microscopic simulation models allow for better consideration of upstream and downstream intersections, the platooning of opposing traffic that generates different gaps in traffic compared to random arrivals, the vehicle type (including heavy vehicles), and the stochasticity of drivers' behaviors.

4.3.10 Actuated Controller Timing Parameters

All tools model a pre-timed and actuated signal controller. The parameters of pre-timed signal control are basic parameters that are modeled by all tools. This section discusses the modeling of actuated signal control parameters in different tools.

Passage Time
Passage time denotes the maximum amount of time one vehicle actuation can extend the green interval when green is displayed for the actuated phase. It is an input for each non-actuated signal phase. This is an input to the HCM/HCS procedure, Vissim, TransModeler and Synchro/SimTraffic.

Maximum Green
This entry specifies the maximum amount of time that a green signal indication can be displayed in the presence of conflicting demand. This is an input to the HCM/HCS procedure, Vissim, TransModeler, and Synchro/SimTraffic.

Minimum Green
This entry specifies the shortest amount of time that a green signal indication will be displayed for a movement. This is a required input in all models.

Yellow and All-Red Duration
All analysis tools except for the HCS procedure require the yellow interval and all-red interval (if used) as inputs. HCS procedures require the input of effective greens that consider the yellow and all-red implicitly. Vissim incorporates fine-tuning driving behavior during yellow and all-red by modifying the driving behavior parameters, where SimTraffic incorporates fine-tune driving behavior during yellow and green intervals. It is not clear if TransModeler can incorporate the fine-tuning of these parameters.

Walk Interval and Pedestrian Clearance
All analysis tools procedures allow this input.

Phase Recall

A phase recall causes the controller to place a call for a specified phase during each cycle, regardless of the prevailing demand. This option is allowed in HCM/HCS and Synchro. In Vissim, there are four options of this feature if specified: Min recall (provide minimum green time), Max recall (provide maximum green time), soft recall (provide continuous green time to a movement when demand/calls from other movements are absent), and pedestrian recall (provide walk plus pedestrian clearance time*)*. In TransModeler, there are three options if specified: Min recall, Max recall, and Pedestrian recall.

Dual Entry

The dual (double) entry parameter is used to call both vehicle phases that can time concurrently even if only one of the phases is receiving an active call. For example, if dual entry is active for Phases 2 and 6 and Phase 2 receives a ***call,*** but no call is placed on Phase 6, Phase 6 would still be displayed, along with Phase 2. This entry is an input to the HCS procedure and affects the estimated green time for a phase. This entry can also be used as input to Synchro, but it is not clear if it is used in SimTraffic. It seems that TransModeler does not have this feature in the input parameters. In Vissim, dual entry is available with the Ring Barrier Controller (RBC) actuated control.

Simultaneous Gap-Out

This entry specifies the manner in which phases are terminated before the barrier can be crossed to serve a conflicting call. If enabled for a phase, then the phase will only gap-out when the other phases with which it is running concurrently have also gapped out (or maxed out). If it is not enabled, then once the phase has gapped out, it will not be allowed to be extended and will terminate as soon as the other phases with which it is running have gapped out or maxed out. This feature can be enabled or disabled in the HCS/HCM, and it impacts the actuated phase time.

Synchro and SimTraffic both allow simultaneous gap-out for both actuated and semi-actuated intersections. Vissim allows for the specification of gap-out for actuated coordinated signal groups and distributes unused time to movements with greater demands. The user can specify simultaneous gap-out for a phase in TransModeler.

Force-Off Mode

For coordinated operations, this entry specifies the force-off mode (fixed or floating), which governs reallocation of green time within the cycle. In HCS, it affects reallocation of green time within the cycle and the amount of available green time available to each movement**.** Vissim with RBC has an option to use the force-off mode per signal group in a coordinated signal timing operation. The force-off feature in Vissim defines the time in seconds measured past the local zero point when the selected green phase will end within the cycle. This value is only used if ExplicitForceOffs is set to “On”; otherwise, automatic force-offs are used as defined by the split and offset reference.

TransModeler also uses this feature. If the Max Inhibit parameter for a phase that has started early is set to Yes, that phase will be allowed to maintain green beyond its split until its fixed force-off time. This way, unused time is allocated to the next non-coordinated phases in the cycle. If no non-coordinated phases have Max Inhibit enabled, floating force-offs are effectively used and all unused time is allocated to the coordinated phase(s).

Synchro/SimTraffic has an option to code it, resulting in Fixed Force-Off, which will give more time to side streets. The Set Fixed Force Off to Off will give all extra time back to the main street.

Finding: All reviewed tools have actuated control models that allow for the inputting of complex actuated controller modeling parameters. Microscopic simulation modeling can better consider the local arrivals' patterns, stochasticity, detection configurations, and controller setting. Vissim allows controller software-in-the-loop and hardware-in-the-loop, allowing for even more realistic modeling of actuated controllers.

4.3.11 Preemption and Priority

The impacts of traffic control strategies like preemption and priority cannot by assessed using HCM/HCS, Synchro, or SimTraffic.

The user can apply the Intersection control editor for the specifications, as well as for more advanced control, such as traffic signal preemption and priority in TransModeler. Preemption has a higher priority than just priority. A signal controller will override a served priority when receiving a preemption call. When signal preemption or priority is granted at a coordinated signal controller, TransModeler will automatically and gradually restore the signal timing to coordinate over one or more cycles following the controller's return to normal operation. Four steps must be taken to implement priority in a model: identify the priority classes, assigning priority classes to routes, adding detectors for signal priority, and defining traffic signal priority settings. TransModeler can also perform the modeling of queue jumping for transit vehicles traveling in a reserved transit lane (e.g., a bus lane) or in a special bypass lane to place calls for a special transit phase that receives green while all conflicting movements receive red.

Vissim has ten built-in prioritized priority and preemptions features, including two track clearance states, dwell state and exit state per preempt. The preemption features permit or allow any signal group and overlap individually for each preempt. There are a number of transit priority options, including extend only, minimum signal group green times, maximum extend limit, and omitting optional vehicle/pedestrian signal groups.

Finding: Advanced control strategies like emergency vehicle preemption, transit signal priority, and freight priority can be modeled in Vissim and TransModeler, but not in the evaluated analytical tools and SimTraffic. TransModeler can model preemption and priority calls, while Vissim can model preemption and priority strategies with different levels of priorities.

4.4 TWO-WAY STOP UNSIGNALIZED INTERSECTIONS (TWSC)

This section provides a comparison of the modeling of two-way stop intersections (TWSC) in different tools. TWSC intersections are unsignalized intersections where drivers on the major street have priority over drivers on the minor-street approaches. Minor-street drivers must stop before entering the intersection. Left-turning drivers from the major street must yield to oncoming major-street through or right-turning traffic, but they are not required to stop in the absence of oncoming traffic.

4.4.1 Intersection Configuration

Three-leg and four-leg intersections can be modeled in the HCM/HCS. HCM/HCS models TWSC intersections with up to three through lanes (either shared or exclusive) on the major-street approaches, and up to three lanes on the minor-street approaches (with no more than one exclusive lane for each movement on the minor-street approach). The major approach may have a maximum of five lanes (1 exclusive left turn or U-turn, 3 through lanes, and 1 exclusive right turn). The user cannot input shared left lane and exclusive left lane simultaneously in the HCS and also cannot input simultaneous shared and exclusive lanes for right turns.

A maximum of eight-leg intersections can be coded in Synchro/SimTraffic. However, the quality of this modeling needs to be checked since this tool was mainly developed for signalized intersection operations.

There is no limitation on the number of lanes and legs in Vissim and TransModeler. Vissim and TransModeler are flexible in allowing the modification of the number of lanes and lane configurations. However, the user has to be very careful to ensure that the model reflects the actual driver behavior under different configurations, which can be a challenging task. It is recommended that an analyst compares the obtained results to those measured in the field and/or those obtained using the HCM procedures. An unsignalized intersection can be modeled in Vissim by using priority rules, conflict areas or stop signs in the model, allowing for any intersection configuration.

The lane width affects the capacity in HCM/HCS procedures and Synchro. However, it does not affect the capacity in Vissim. The default value of lane width used in TransModeler is 12 feet for all lanes. If the lane widths are modeled, there is no effect on operations in TransModeler for lanes specified with widths greater than 12 feet.

Finding: Vissim and TransModeler are more flexible in inputting various configurations of TWSC. However, the user needs to examine the operations of the simulated intersections to ensure that it replicates real-world priority rules. The resulting capacity from these simulation models can also be compared with HCS procedures to ensure that they produce the same capacities for the same conditions if real-world capacity data is not available. The TransModeler appears to have the ability to automatically account for lane width. The SimTraffic simulation of unsignalized intersections should be carefully examined since this program was originally developed as a signalized intersection model.

4.4.2 Approach Grades

The HCS/HCM and Synchro allow for the inputting of the percent grade for each approach for use in computing an adjustment factor of the critical headway and follow-up headway. This parameter impacts capacity. Vissim, TransModeler, and SimTraffic allow for the inputting of upgrades and downgrades of a link, which impact vehicle performance and thus capacity, considering heavy vehicle presence.

Finding: All tools allow for the inputting of upgrades and downgrades. The user should recognize that the HCM procedures assume certain types of trucks and may not produce accurate impacts if the truck composition is different. Vissim, TransModeler, and SimTraffic are more flexible in specifying the truck composition and thus the impacts on grades. However, the results from these models need to be verified and calibrated.

4.4.3 Additional Geometry Features

The HCS/HCM allows for the inputting of an exclusive left-turn bay (the range of let-turn storage in HCS is from 0 to 9 vehicles), flared approach on the minor street with a shared right-turn lane that allows right-turning vehicles to complete their movement while other vehicles are occupying the lane, the length of a pedestrian crosswalk, presence of a raised median to allow a two-stage crossing, and main street right-turn channelization. Synchro users can also input the above-mentioned features. However, it appears that inputting an exclusive left-turn bay has no impact on delay or capacity in Synchro or SimTraffic. As per the Synchro Manual, the user can specify a through lane with a small right turn lane with a storage of 25-75 ft to approximate the flared approach on the minor street. Right-turn channelization can be coded as free, yield, stop and signalized in Synchro. Vissim and TransModeler are flexible in allowing for the inputting of the above geometry features.

Finding: Vissim and TransModeler are more flexible in the inputting of various configurations of TWSC. However, the user needs to examine the operations of the simulated intersections to ensure that it replicates real-world priority rules.

4.4.4 Two-Stage Gap acceptance

The HCM/HCS allows for the inputting of median storage on the main street to allow two-stage gap acceptance. The range of the number of vehicles that are able to be stored in the median to use the two-stage gap acceptance is from 1 to 9 vehicles in HCS. Synchro allows for the consideration of this capability only as part of the HCM 6th Edition option with the range of the variable from 0 to 2 vehicles. If the Median Width on the main street is larger than the average vehicle length (set in the Network Settings), then two-stage calculations will be performed in Synchro. SimTraffic is not able to model two-stage gap acceptance.

This feature can be modeled in Vissim by manipulating intersection configuration, stop location, and priority rules. In TransModeler, the road editor is used to add a refuge area within the major street median to allow for queuing storage during two-stage crossing maneuvers.

Finding: HCM 2016, Vissim, and TransModeler allow two-stage gap acceptance at TWSC. Synchro can model this feature only when requesting the HCM 2016 analysis option. SimTraffic does not model this feature.

4.5 FREEWAY FACILITIES

This section presents a discussion on the modeling of freeway facilities in different analysis, modeling, and simulation tools. It should be noted that although the Synchro/SimTraffic Manual suggests that freeway merges and their interactions with signal control can be modeled using the tool, this tool is really a signalized arterial modeling tool and thus will not be addressed further in this section.

4.5.1 Basic Freeway Segments

Several features of a basic freeway segment are compared in this section including free flow speed, geometry impacts, grade impacts, managed lane geometry, driver characteristic, lane blockage modeling, and weather modeling. These features also impact the weaving segments and the merge/diverge segments.

Free Flow Speed
The HCM/HCS procedures model freeway segments with an average free flow speed (FFS) in the range of 55 mph to 75 mph. The FFS as measured in the field can be provided by the user or calculated by the HCM. When estimated by the HCM procedure, the basic free flow speed is adjusted according to HCM to account for various geometry features, as discussed later in this section.

Vissim allows users to input the desired speed distribution for each vehicle type, in addition to the maximum speed for each segment. These values together allow for the estimation of individual vehicle speeds. TransModeler allows changes to the free flow speed of the segment. TransModeler also has a speed distribution that defines what percentage of drivers will deviate what amount of speed from the speed limit of the segment.

Finding: The HCS/HCM procedure allows for the inputting of an average free flow speed by segment. On the other hand, Vissim and TransModeler use free flow speeds that vary by vehicle type with a stochastic variation of these speeds, resulting in different free flow speeds for individual vehicles in the simulation.

Freeway Geometry Impacts
The number of freeway mainline lanes ranges from two to nine lanes in the HCM/HCS. TransModeler allows for a maximum of 16 lanes in one direction. There is no limit on the number of lanes in Vissim. The lane width in the HCM/HCS is used to measure the adjusted free flow speed, which impacts the capacity per lane and ranges from 10 ft to 12 ft. The lane width can be modified in TransModeler, and the analysis in this study indicates that wider lanes result in higher average speeds. The user can define the lane width in Vissim, but the lane width has no impact on traffic flow or capacity. Thus, the speed should be changed by the user to reflect the impact of the lane width.

Another parameter that can be modified in the HCM/HCS is the right-side lateral clearance, which can affect the FFS and thus capacity. This parameter is the distance from the rightmost travel lane to fixed obstructions on a freeway; it is measured in feet and has a range from 0 ft to 10 ft. A right-side shoulder can be specified in TransModeler. Adding/increasing the width of the shoulder increases the average speed. This feature is not considered in Vissim and thus its impact on speed has to be explicitly specified by the user.

Another parameter that impacts the free flow speed in the HCM/HCS procedure is the total ramp density, which is the average number of on-ramp, off-ramp, major merge, and major diverge junctions per mile. This parameter impacts the FFS estimation. Vissim and TransModeler have no options to input this parameter. However, this impact is expected to be reflected as a result of the microscopic interactions between vehicles.

Finding: The HCS/HCM procedure considers the impacts of a number of features, including lane width, lateral clearance, and the proximity of other interchanges. The proximity of other interchanges is assessed based on the microscopic interactions of vehicles in Vissim and TransModeler. TransModeler considers the impact of lane width and shoulder width on speed. However, these impacts have to be input manually by the user in Vissim.

Managed Lane Geometry

The HCM/HCS procedure includes a managed lane procedure that considers the specific attributes of the managed lanes (ML) and the interaction between the ML and general-purpose lanes. The HCM considers five types of separations between the ML and GPL when estimating the ML capacity. These types of separation are continuous access, skip-stripe or solid strip separated with single lane, buffer-separated with single lane, buffer-separated with multiple lanes, barrier-separated with single lane, and barrier-separated with multiple lanes.

Vissim and TransModeler allow for the restriction of specific lanes for use by certain types of vehicles. However, they do not consider the specific characteristics of ML and the separation of the ML and GPL.

Findings: The HCM includes a detailed procedure based on a research effort that considers the specific characteristics of ML and the separation of the ML and GPL. This is not considered in simulation models. It is useful to incorporate the impacts derived based on the HCM ML procedures, particularly the impact of the ML separation type, in conjunction with the modeling of ML in the simulation tools.

Driver Population Type

Driver population describes the level of driver familiarity in the traffic stream and is used in adjustments for speed and capacity. It has five categories in the HCM/HCS. It affects both the speed and capacity adjustment factors. Vissim and TransModeler do not consider these parameters.

Findings: If the user measures the free flow speed and capacity in the field, then the simulation model can be calibrated to produce these values. If this is not possible (for example in the case of future geometry), the user should consider this factor in estimating capacity and use the results to fine-tune the car-following parameters in the models to produce the capacity.

Weather, Incident, and Work Zone Impacts

The HCM can estimate the impacts of weather, incidents, and work zones on free flow speed and capacity. The HCM considers several types of weather conditions: covering snow, rain, and low visibility. The HCM can also estimate the impacts of several types of incidents and work zones on capacity. The HCM calculates the highway capacity in the presence of work zones considering the lane closure type (number of closed lanes and percent of closed lanes), area type (urban and rural), time of the day (daytime vs. nighttime), barrier type (concrete and hard barrier separation; and cone, plastic drum, or other soft barrier separation), lateral distance in work zone, speed limit at work zone, and capacity drop percentage due to queuing. The HCM/HCS procedure also differentiates between short-term and long-term work zones since there may be a learning effect for drivers that increases capacities over time. Research shows an average queue discharge drop of 7% in non-work zone conditions, and an average value of 13.4% in freeway work zones. When there is little local information available on the capacity drop, these values can be used as defaults.

Vissim does not consider weather, incident, and work zone conditions; however, these impacts can be modeled by blocking lanes and fine-tuning the model parameters to replicate the impacts.

TransModeler allows for the input of lane closures due to work zones or incidents, including the number of lane closures, length of the closed lanes, duration of the closure, and desired speed in the nearby lanes when modeling work zones or incidences. TransModeler does not model the impacts of weather; however these impacts can be modeled by fine-tuning the model parameters to replicate the impacts.

Findings: The HCM includes speed and capacity adjustment factors for the impacts of adverse weather events, incidents, and work zone conditions. It is recommended that the user apply the estimated capacities and free flow speeds obtained from the HCM procedures to inform the simulation analysis. TransModeler has a lane blockage model for use in assessing incident and work zone impacts. Although not explicitly modeled, the impacts of these lane blockages can be emulated in Vissim.

4.5.2 Weaving Segments

Weaving segment configuration significantly affects the performance of the segment. The configuration of a weaving segment refers to the way that entry and exit lanes are linked and how many lanes changes a weaving driver must make to complete the weaving maneuver successfully. There are specific weaving configurations in the HCM/HCS. On the other hand, simulation tools are very flexible in modeling several types of weaving segments. However, the simulation model parameters have to be fine-tuned to ensure that the weaving segments are correctly simulated.

All tools allow for the inputting of demand flow, including mainline to mainline, mainline to ramp, ramp to mainline, and ramp to ramp. The HCM does not consider upstream or downstream ramps, intersections, and bottlenecks that may affect the weaving operations. Simulation models can consider the impacts of multiple ramps in the vicinity of the weaving area.

The FDOT Traffic Analysis Handbook has a chapter on the analysis of Express Lanes. This chapter has a section on the simulation of complex and multiple weave segments that are formed by a series of closely spaced merge and diverge areas creating overlapping, weaving movements between different merge-diverge pairs that share the same roadway segment. Such weave segments are formed by the left-side access from express lanes to general use lanes. The modelers need to examine the ability of TransModeler and Vissim to apply the FDOT procedure mentioned above. Such complex weaving segments cannot be analyzed using the HCM/HCS procedure.

Finding: The HCM/HCS has procedures to analyze weaving segments that were derived based on empirical data. The data was collected for specific configurations, and the procedures do not consider the upstream and downstream interchanges, intersections, and bottlenecks on the operation. Simulation models are flexible in modeling various weaving configurations and impacts of adjacent bottlenecks and junctions. However, the modeler needs to be very careful in ensuring that the model is accurately simulating the weaving segment. The FDOT weaving segment simulation procedure presented in the 2016 Traffic Analysis Handbook should be used. The modelers need to examine the ability of TransModeler and Vissim to apply the FDOT procedure mentioned above. Such complex weaving segments cannot be analyzed using the HCM/HCS procedure.

4.5.3 Merging and Diverging Segments

The HCM has procedures to analyze the on-ramp merge area and off-ramp diverge area and assume that the length of the segment that is influenced by the merge and diverge is 1,500 ft. The HCM also considers if a ramp upstream or downstream of the analysis ramp is close enough to affect the ramp-freeway merge or diverge operations. The HCM assumes that adjacent ramps with a distance of over 8,000 ft have no impacts.

Simulation models can simulate the merging and diverging operations, including the impacts of multiple ramps in the vicinity of the existing ramp and their interactions with signalized intersections on the surface street. In Vissim and TransModeler, the user can change the point at which the user starts changing lanes ahead of the off-ramp and on-ramp merging ability. However, the user has to be careful in calibrating the performance of these operations by comparing to it real-world data and/or HCM procedure results. It is critical that the user ensure that the lane change behaviors in the merge and diverge area are well calibrated. Vehicle trajectory data should become available in the next few years to allow such calibration, particularly with the increased market penetration of connected vehicles. In the absence of vehicle trajectory data, the resulting capacity from simulation models should be at least compared with those resulting from the HCM procedures. TransModeler considers the ramp influence of 1,500 ft in its estimation of density and level of service and will produce a warning for any link with a ramp that has a length greater that 1,500 ft.

The length of the on-ramp acceleration and off-line deceleration lanes can be modified in all tools, including the HCM/HCS, Vissim, and TransModeler.

Finding: The HCM has procedures to analyze the merge and diverge areas within 1,500 ft of the on-ramps and off-ramps. Simulation models are flexible in modeling these operations and the impacts of adjacent bottlenecks, junctions, and congestion. However, the modeler needs to be very careful in ensuring that the model is accurately simulating the lane changing behaviors in these areas. The user should calibrate the model based on real-world data and HCM procedure results. The availability of trajectory data from connected vehicles and advanced sensor technologies will assist in better calibration of the models.

4.6 CONNECTED AND AUTOMATED VEHICLES

This section describes connected and automated vehicle (CAV) modeling in the compared tools. Neither Synchro or SimTraffic have features that model connected and automated vehicles, and thus they will not be further discussed in this section.

4.6.1 Modeled CAV Features

There are a large number of CAV applications that can be assessed using simulation tools or extensions to these simulation tools, as discussed in Chapter 3. The HCM procedure allows for the analysis of a subset of CAV features such as cooperative adaptive cruise control (CACC), platooning, and dynamic merge control. The current HCM procedure is only applicable to basic freeway, merge, diverge and weaving segments, and does not include the capacity estimation due to CAV on arterial streets, freeway with managed lane segments, and performance during traffic breakdown conditions. Depending on how these features are implemented, they can be considered Society of Automotive Engineers Level 1 or 2. There are a large number of mobility, safety, and environmental impact applications and features of connected, automated, and cooperative driving automation other than the ones modeled by the HCM/HCS procedures. These applications and features cannot be modeled using the HCM/HCS procedures.

The Vissim simulation of CAVs mainly addresses the car-following capabilities of CAV, which reflects the improvement in driving performance with automated driving. Vissim uses the Wiedemann's model to simulate the car-following behaviors of vehicles. For CAVs, Vissim has a built-in car-following model with different headways and standstill distances, and the user specifies the CAV vehicle types and classes that can be used to model the combinations of CAV vehicle-driving behaviors. Three different levels of driving behaviors can be modeled. These behaviors are cautious (with higher headway), normal (similar headway of human driven vehicle), and all-knowing (with shorter headway). The details of these three driving behaviors are shown in Table 4-3. Vissim has CAV-specific acceleration characteristics and absolute braking distance that denotes the distance required for CAVs braking if the leading vehicle stops instantly. Vissim also has a built-in AV platooning model, which allows for the specification of the number of vehicles, speed, max distance, gap time and minimum clearance in platooning. Vissim also has a built-in lane changing behavior for CAVs, where the user can modify several parameters replicating the impact of CAVs. The default CAV driving behavior parameters were developed based on empirical data that PTV collected on a test track in Helmond, Netherlands, combined with car and traffic co-simulations efforts. The collected data was not available for lane changing, and the default values were set based on assumptions for lane changing. The longitudinal and lateral movements of CAVs in addition to many other CAV applications can be modeled by using COM or External Driver Model Algorithms.

Table 4-3 The three CAV driving behaviors in Vissim

Parameters	Human Driven Default	Cautious	Normal	All-Knowing
Car-Following Parameters				
CC0: Standstill Distance	1.5	1.5	1.5	1.0
CC1: Headway Time	0.9	1.5	0.9	0.6
CC2: Following Variation	4.0	0.0	0.0	0.0
CC3: Threshold for Entering Following	-8.0	-10.0	-8.0	-6.0
CC4: Negative Following Threshold	-0.4	-0.1	-0.1	-0.1
CC5: Positive Following Threshold	0.4	0.1	0.1	0.1
CC6: Speed dependency of Oscillation	11.4	0.0	0.0	0.0
CC7: Oscillation Acceleration	0.3	0.1	0.1	0.1
CC8: Standstill Acceleration	3.5	3.0	3.5	4.0
CC9: Acceleration with 80 km/h	1.5	1.2	1.5	2.0
Lane Change Parameters				
Maximum Deceleration Own	-4	-3.5	-4	-4
Maximum Deceleration Trailing Vehicle	-3	-2.5	-3	-4
-1 m/s^2 per distance Own	200	80	100	100
-1 m/s^2 per distance Trailing Vehicle	200	80	100	100
Accepted Deceleration Own	-1	-1	-1	-1
Accepted Deceleration Trailing Vehicle	-0.5	-1	-1	-1.5

TransModeler allows for the modeling of vehicles with different SAE automation levels with different percentages. TransModeler uses the Modified General Motors (GM) for modeling the non-connected automated vehicles and the Constant Time Gap model for the modeling of the CAV. In TransModeler, the head buffers, variance of acceleration, modified GM car-following model headway threshold, and stopped gap distances are altered to emulate Level-1A (acceleration) automation. Then, random error terms in the lane changing gap acceptance model and sensitivity to lane connector connectivity bias are altered to emulate Level-1B (steering) automation. The parameters for both Level-1A and Level-1B are altered for Level-2 AV. The desired speed model is additionally adjusted to model Level-3 automation in TransModeler. The tool documentation states that Level 4 and 5 automations are subject to user customization using the API.

With zero automation, TransModeler simulates the vehicles according to the acceleration, lane changing, and gap acceptance behavior models of normal vehicles that include a random error term in the lane changing gap acceptance model. All random error terms related to gap acceptance in the lane changing model are eliminated in Level-2 AV. When Level 3 automation is simulated, additional aspects of driving beyond routine normal acceleration and lane changing tasks are placed under the control of the vehicle and removed from the decision model representing driver decision-making. Most notably, the desired speed will no longer follow the desired speed distribution. Rather, every vehicle with Level 3 automation will choose the posted, or regulatory speed limit as its desired speed.

Finding: The latest version of the HCM allows for the simulation of CACC, platooning, and dynamic merge control on freeway segments. The parameters of the modeling were derived based on Vissim simulation results combined with observed CAV driving behavior in a prior test. The procedures do not consider non-connected automated vehicles, operations on arterial streets, and the specific impacts of managed lane driving. Vissim and TransModeler introduced new driving behaviors that can be used to model the longitudinal movements, lateral movements, and combinations of these movements. It appears that the default parameters were derived based on limited data, and further research is needed to confirm and extend these models. There is a large number of mobility, safety, and environmental impact applications and features of connected, automated, and cooperative driving automation other than the ones modeled by the HCM/HCS procedures and the built-in procedures in the traffic simulation tools. These features can be modeled using the API facilities in the simulation tools and various software-in-the-loop and hardware-in-the-loop configurations.

4.6.2 Desired Speed Distribution

The user can use and modify specific FFS distributions for CAV in Vissim and TransModeler. For a human-driven vehicle (HDV), the fluctuation of the desired speed is high, resulting in wider speed distributions compared to CAV. For the CAV, Vissim has a narrow default speed distribution. For example, the speed varies from 60-75 mph for an FFS of 65 mph for HDV. For CAV, the default speed values vary from 63.76 mph to 66.24 mph for an FFS of 65 mph. TransModeler assumes that the desired speed will no longer follow the desired speed distribution at Level 3 automation, and that vehicles with this level of automation will choose the posted, or regulatory, speed limit as its desired speed.

Finding: The desired speed is an important parameter that impacts simulation results. Vissim uses narrower default speed distributions for the CAV. On the other hand, TransModeler only removes the stochasticity of the desired speed from the Level 3 automation.

4.6.3 CAV Market Penetrations and Exclusive Lanes

All tools allow for the analysis of different CAV market penetrations from 0% to 100%. The user can also specify lanes for the exclusive use of CAV.

Finding: All assessed tools can model the different market penetrations of CAVs. TransModeler and Vissim have the advantage of the ability to include mixtures of CAVs with the different characteristics and levels of automation and connectivity that consider the expected changes in the market penetrations of these technologies through the years. All tools will allow for the modeling of exclusive lanes for CAV.

4.6.4 Volume Ratio in Weaving Segments

This is the ratio of weaving volume to total demand volume in the weaving segment. For CAV, the HCM limits this volume ratio from 0.2 to 0.4. There is no restriction on this ratio in Vissim and TransModeler.

Finding: The user needs to understand the limitations of the analysis in each tool. For example, for CAV, the HCM limits the weaving volume ratio to total demand volume from 0.2 to 0.4.

4.7 SUMMARY OF COMPARISON BASED ON DOCUMENTATION REVIEW

The previous sections of this chapter presented a comparison between the analysis capabilities of a number of deterministic tools and simulation tools based on the documentation of these tools. The compared deterministic tools are the HCS and Synchro. The compared simulation tools are Vissim, TransModeler, and SimTraffic. The comparison presented in this report shows that deterministic modeling procedures and tools like the HCM/HCS and Synchro are adequate in when modeling isolated segments or intersections and for facilities with lower level of congestion and less complex geometries and configurations. In fact, the HCM procedures can be used as a basis to confirm the assessed capacity in the simulation models in the absence of field data and potentially fine-tunes the simulation model parameters based on the results of the comparison. This can include for example fine tuning the parameters to obtain capacities comparable to HCM estimates considering various geometric elements, signalized and unsignalized intersection control, weaving segments, merging and diverging segments, express lanes, permissive left-turn, and so on. Simulation models should be used for congested conditions, conditions with queue spillbacks and spillovers, the interactions between freeway and arterial facilities, networks with complex geometry and configuration that cannot be adequately analyzed using the HCM, transit and non-motorized user modeling, active and demand management modeling, extended capabilities for CAV modeling, and situations that require multiresolution analysis and dynamic traffic assignment.

The SimTraffic model is more basic compared to the other two microscopic models. SimTraffic cannot model freeway segments and the interaction between freeway and arterial facilities, has more basic car following and lane changing models compared to the other two models, less advanced unsignalized intersection modeling, no capabilities for dynamic traffic assignment and multiresolution modeling, no capabilities to model traffic routes between origins and destinations, no capabilities for traffic and demand management modeling, no capabilities for CAV modeling, no ability to model bus routes and operations, no ability to model non-motorized traffic, no ability to model express lanes and pricing, and no ability to model emergency vehicle preemption and bus priority.

The followings are the specific findings from the comparison.

1. The HCM/HCS procedures can be used to analyze local intersections and segments, in addition to linear freeway and arterial segments. In addition, Synchro and SimTraffic documentation stated that these tools can model grid street networks. Synchro and SimTraffic cannot model freeway segments. The HCM/HCS has procedures to model rural two-lane and four-lane highways. The HCM/HCS, Synchro, and SimTraffic cannot model an integrated network of freeways and arterial streets. A main advantage of Vissim and

TransModeler is their ability to model a network of model freeways and arterials and their interactions. TransModeler can also model two-way two-lane rural highways.

2. Traditionally, the HCM/HCS procedures for isolated intersections and segments have been developed to analyze the peak 15 minutes within the peak period. However, the freeway and arterial facility procedures developed later allow for the modeling of multiple periods, although the length of the period is still generally fixed at 15 minutes. Synchro, SimTraffic, TransModeler and Vissim are flexible in simulating multi-periods with varying lengths.

3. The HCM/HCS, Synchro, and SimTraffic require the inputting of the turning movement volumes or percentages of the approach volume at each intersection and ramp. The users of Synchro and SimTraffic can also specify “local pairing” of volumes between a pair of upstream and downstream intersections. An advantage of Vissim and TransModeler is the ability to model the traffic from their origins to their destinations, although both allow for the inputting of turning movement counts if the user prefers. Both Vissim and TransModeler can accommodate dynamic traffic assignment. Vissim allows several other advanced routing methods that can be used to ensure better replication of the routes from origins and destinations if the dynamic traffic assignment option in the tool is not used. These routes can be identified based on higher level assignment models such as those incorporated in Vissim.

4. Synchro and the HCM/HCS apply factors to reduce the saturation flow rates and capacities based on the proportion of trucks in the traffic stream. However, these factors assume one type of truck with specific power to weight ratio for arterial analysis, and two types of trucks with specific power to weight ratios for the HCM freeway analysis. SimTraffic can model four types of trucks. The user can vary the proportion, acceleration, and dimensions of these vehicles. TransModeler can model three types of trucks: single unit truck, trailer truck and the user can specify the mean, standard deviation, and distribution of the mass and power parameters for each vehicle class. Vissim can specify the distribution of the length, weight, power, and acceleration/deceleration characteristics of vehicle classes (including heavy vehicles) with no limitations on the number of the truck types in the program. If the trucks are expected to have significant impacts on system performance, the user needs to identify the truck type mix in the traffic stream, determine if the analysis tool allows for the inputting of this mix, and then examination of the impact on the performance of the truck mix based on whether the simulation results are logical.

5. Synchro/SimTraffic and the HCM/HCS consider the impacts of upstream bus stops in the close proximity to the intersection on the saturation flow rate. However, they do not explicitly model bus operations and the detailed interaction of individual buses with the traffic. Vissim and TransModeler can model the different types of buses and trains, including routes, bus stops, and dwell times at bus stops. These simulation tools can estimate the performance of the public transit routes.

6. The user can specify non-motorized traffic in HCM/HCS and Synchro/SimTraffic to be used in estimating the impacts of the conflicts with the turning vehicles on the saturation flow rates of the turning movements, as well as to estimate the changes in the actuated signal timing due to pedestrian phase activation. However, non-motorized traffic, including

individual pedestrians or bicycles, are not explicitly modeled to be able to determine the stochasticity of their operations or to derive the performance measures associated with these operations, as can be done with Vissim and VisWalk. Although TransModeler can model the effect of pedestrian on vehicular traffic capacity, it does not produce pedestrian performance measures.

7. Vissim implements the Wiedemann car-following model, which is a recognized car-following model. TransModeler allows using the GM model, Gipps model, Wiedemann models, and Intelligent Driver model, which is a nice research capability. The vendor can provide guidance as to when these models should be used in practice.

8. The HCM/HCS and Synchro as macroscopic tools do not explicitly model lane changing, although the HCM implicitly considers the impacts of lane changing in their merge, diverge, and weaving freeway segments. Both Vissim and TransModeler have detailed mandatory lane change (MLC) and discretionary lane change (DLC) with multiple parameters that can be fine-tuned. SimTraffic only allows MLC (no DLC), and the lane changing model is simplified with only two parameters.

9. Although the HCM/HCS and Synchro procedures can consider the impact of congestion and spillbacks, the operations under oversaturated conditions and the spatial and temporal influences of congestion are base modeled using microscopic simulation models. These models have the ability to model the queue growth from one interval to the next. They can also model oversaturation and spillover from the turn bays to adjacent lanes, and from one segment to the next. Additional advantages of simulation models are their ability to consider the impact interactions of upstream and downstream bottlenecks, and downstream hidden bottlenecks that can appear after solving the upstream bottlenecks.

10. Synchro and HCM/HCS procedures use average desired speeds for a link and do not consider in detail the variations in individual vehicle speeds on performance, although the HCM arterial street facility procedure has a platoon dispersion algorithm that considers the change in the platoons as they progress from upstream to downstream signals. TransModeler, Vissim, and SimTraffic allows for the changing of speed by link and vehicle/driver types. In TransModeler, users can input speed limits for 21 road classes (freeway, rural highway, expressway, weaving, system ramp, collector-distributor, ramp, minor arterial, major arterial, minor collector, major collector, local street, access road, trail road, roundabout, tunnel, rail, waterway, freeway-piecewise linear and freeway-Van Aerde), each of which may follow six desired speed distributions (standard, school zone, work zone, freeway, major and minor arterial). TransModeler and Vissim have more flexibility in assigning speeds to more vehicle/driver types. In addition, it seems that SimTraffic does not consider the stochasticity of speed for each vehicle type.

11. Advanced operations, active management, demand management, and pricing strategies are best analyzed using advanced simulation tools like Vissim and TransModeler. These programs have API facilities that can integrate codes to emulate these strategies with the simulation models. Vissim has the ability to have co-simulation that involves software-in-the-loop, hardware-in-the-loop (e.g., signal controller in the loop), human-in-the-loop, and/or vehicle-in-the-loop (including human-driven and connected and automated

vehicles). TransModeler may have at least some of these capabilities, but this has to be investigated. SimTraffic allows interfaces with controller-in-the-loop but does not allow the modeling of advanced strategies or additional co-simulation options.

12. The HCM/HCS has a limit on the number of approaches and lane groups that can be analyzed a (maximum of four legs and a maximum of three lane groups per approach). Other examined analysis tools do not have this limitation. Lane width impacts capacity in the HCM/HCS, Synchro, and TransModeler. The lane width does not affect capacity in the Vissim and thus this impact has to be approximated by manipulating other input parameters. It is not clear if SimTraffic can simulate the impact of lane width. The impact of the reduction in the lanes on the departing (receiving) approach on vehicular traffic capacity cannot be accurately modeled using analytical/deterministic tools; they can best be modeled using simulation models.

13. The imbalance in lane utilization can affect the performance of the signalized intersection. The HCS/HCM and Synchro have default values for lane utilization. Vissim and TransModeler assign the traffic to lanes based on their downstream turns. In addition, TransModeler can use the lane utilization factor from the HCM and input a factor to bias the traffic towards specific lane(s), which is a nice feature to have if it works correctly. It is not clear of how well SimTraffic assigns traffic to lanes. If the user inputs the upstream-downstream demand pairs between upstream and downstream intersections, one may think that the model may be able to assign the vehicles to lanes considering this pairing. However, this is not certain and needs to be tested.

14. Upgrades and downgrades impact capacity in the HCM/HCS, Synchro, Vissim, and TransModeler. The impact of the change in capacity with different truck proportions and compositions in different tools should be examined.

15. Left- and right-turn radii are used as inputs to HCS/HCM, and Synchro and these values affect the capacities of the associated movements. All three microsimulation models use turn speeds rather than turn radii to impact capacity. TransModeler also allows for the inputting of turn radii. The user should examine how the turning speeds in each of the microscopic simulation tools impact capacity.

16. The HCM/HCS arterial street procedure applies a macroscopic platoon dispersion model to estimate the arrival on green at the downstream signal based on the link speed, offset, distance between the upstream signal timing, and the implemented platoon dispersion model. Synchro determines the platoon arrival on green based on the link speed and the distance between the upstream signal timing. However, it does not implement a platoon dispersion model. Coordination and offset impacts are modeled in detail in Vissim, TransModeler, and SimTraffic as the individual vehicles progress from the upstream signal to the downstream signal.

17. The modeling of shared lanes is challenging. Synchro and HCM/HCS have models for estimating the capacities of these lanes but require the user to input the number of vehicles that use the shared lane when there is an adjacent exclusive lane that can be used by the vehicles. Microscopic simulation models assign the vehicles to the shared lanes based on

downstream/upstream lane changing. The lane assignment and the resulting capacity estimates need to be further examined by the users. SimTraffic does not seem to consider the impact of a shared lane.

18. In situations where midblock constraints and frictions such as the case with parking activities, work zones, incidents, and parking impact traffic, models like Vissim and TransModeler are recommended. TransModeler has a detailed built-in on-street parking model.

19. HCM/HCS and Synchro have detailed permissive left-turn models that can provide good estimates of capacity. The microscopic simulation models allow for better consideration of upstream and downstream intersections, the platooning of opposing traffic that generates different gaps in traffic than random arrivals, the vehicle type (including heavy vehicles), impacts of upstream and downstream congestion, and the stochasticity of drivers' behaviors. It is recommended that when using simulation models to confirm the resulting capacity versus those obtained from the HCM, the difference for basic traffic conditions is explained in detail.

20. HCM/HCS requires the inputting of the RTOR capacity, which is difficult to estimate. Synchro has a macroscopic model that can provide estimates of RTOR capacity. The microscopic simulation models have better consideration of upstream and downstream intersections, the platooning of opposing traffic that generates different gaps in traffic compared to random arrivals, the vehicle type (including heavy vehicles), and the stochasticity of drivers' behaviors.

21. All reviewed tools have actuated control models that allow the inputting of complex actuated controller modeling parameters. Microscopic simulation modeling has better consideration of the local arrivals' patterns, stochasticity, detection configuration, and controller setting. Vissim allows controller software-in-the-loop and hardware-in-the-loop, which allows for even more realistic modeling of actuated controllers.

22. Advanced control strategies like emergency vehicle preemption, transit signal priority, and freight priority can be modeled in Vissim and TransModeler, but not in the evaluated analytical tools and SimTraffic. TransModeler can model the preemption and priority calls, while Vissim can model ten preemption and priority strategies with different levels of priorities.

23. Vissim and TransModeler are more flexible in inputting various configurations of TWSC. However, the user needs to examine the operations of the simulated intersections to ensure that it replicates real-world priority rules. The resulting capacity from these simulation models can also be compared with HCS procedures to ensure that they produce the same capacities for the same conditions if real-world capacity data is not available. TransModeler appears to have the ability to automatically account for lane width. SimTraffic simulation of unsignalized intersections should be carefully examined since this program was originally developed as a signalized intersection model.

24. All tools allow for the inputting of upgrades and downgrades. The user should recognize that the HCM procedures assume certain types of trucks and may not produce accurate impacts if the truck composition is different. Vissim, TransModeler, and SimTraffic are more flexible in specifying the truck composition and thus the impacts on grades. However, the results from these models need to be verified and calibrated.

25. Vissim and TransModeler are more flexible in inputting various configurations of TWSC. However, the user needs to examine the operations of the simulated intersections to ensure that it replicates the real-world priority rules.

26. HCM 2016, Vissim, and TransModeler allows two-stage gap acceptance at TWSC. Synchro can model this feature only when requesting the HCM 2016 analysis option. SimTraffic does not model this feature.

27. The HCS/HCM procedure allows for the inputting of an average free flow speed by segment. On the other hand, Vissim and TransModeler use free flow speeds that vary by vehicle type with a stochastic variation of these speeds resulting in different free flow speeds for individual vehicles in the simulation.

28. The HCS/HCM procedure considers the impacts of a number of features, including lane width, lateral clearance, and the proximity of other interchanges. The proximity of other interchanges is assessed based on the microscopic interactions of vehicles in Vissim and TransModeler. TransModeler considers the impact of lane width and shoulder width on speed. However, these impacts have to be input manually by the user in Vissim.

29. The HCM includes a detailed procedure based on a research effort that considers the specific characteristics of ML and the separation of the ML and GPL. This is not considered in simulation models. It is useful to incorporate the impacts derived based on the HCM ML procedures, particularly the impact of the ML separation type, in conjunction with the modeling of ML in the simulation tools.

30. If the user measures the free flow speed and capacity in the field, then the simulation model can be calibrated to produce these values. If this is not possible (for example, in the case of future geometry), the user should consider this factor in estimating capacity and use the results to fine-tune the car-following parameters in the models to produce the capacity.

31. The HCM includes speed and capacity adjustment factors for the impacts of adverse weather events, incidents, and work zone conditions. The recommendation to the user is to apply the estimated capacities and free flow speed obtained from the HCM procedures to inform the simulation analysis. TransModeler has a lane blockage model for use in assessing incident and work zone impacts. Although not explicitly modeled, the impacts of these lane blockages can be emulated in Vissim.

32. The HCM/HCS has procedures to analyze weaving segments that were derived based on empirical data. The data was collected for specific configurations, and the procedures do not consider the upstream and downstream interchanges, intersections, and bottlenecks on the operation. Simulation models are flexible in modeling various weaving configurations and impacts of adjacent bottlenecks and junctions. However, the modeler needs to be very

careful in ensuring that the model is accurately simulating the weaving segment. The FDOT weaving segment simulation procedure presented in the 2021 Traffic Analysis Handbook should be used. The modelers need to examine the ability of TransModeler and Vissim to apply the FDOT procedure mentioned above. Such complex weaving segments cannot be analyzed using the HCM/HCS procedure.

33. The HCM has procedures to analyze the merge and diverge areas within 1,500 ft of the on-ramps and off-ramps. Simulation models are flexible in modeling these operations and the impacts of adjacent bottlenecks, junctions, and congestion. However, the modeler needs to be very careful in ensuring that the model is accurately simulating the lane changing behaviors in these areas. The user should calibrate the model based on real-world data and HCM procedure results. The availability of trajectory data from connected vehicles and advanced sensor technologies will assist with better calibration of the models.

34. The latest version of the HCM allows for the simulation of CACC, platooning, and dynamic merge control on freeway segments. The parameters of the modeling were derived based on Vissim simulation results, combined with observed CAV driving behavior in a prior test. The procedures do not consider non-connected automated vehicles and the specific impacts of managed lane driving. Vissim and TransModeler introduced new driving behaviors that can be used to model the longitudinal movements, lateral movements, and combinations of these movements. It appears that the default parameters were derived based on limited data, and further research is needed to confirm and extend these models. There is a large number of mobility, safety, and environmental impact applications and features of connected, automated, and cooperative driving automation other than the ones modeled by the HCM/HCS procedures and the built-in procedures in the traffic simulation tools. These features can be modeled using the API facilities in the simulation tools and various software-in-the-loop and hardware-in-the-loop configurations.

35. The desired speed is an important parameter that impacts simulation results. Vissim uses narrower default speed distributions for the CAV. On the other hand, TransModeler removes the stochasticity of the desired speed only from Level 3 automation.

36. All assessed tools allow for the modeling of different market penetrations of CAVs. TransModeler and Vissim have the advantage of the ability to include mixtures of CAVs with different characteristics and levels of automation and connectivity that consider the expected changes in the market penetrations of these technologies over time. All tools will allow for the modeling of exclusive lanes for CAV.

37. The user needs to understand the limitations of the analysis in each tool. For example, for CAV, the HCM limits the weaving volume ratio to total demand volume from 0.2 to 0.4.

38. Among the three compared simulation tools in this study, only Vissim and TransModeler have dynamic traffic assignment and multiresolution modeling capabilities. These capabilities will be compared in Task 4 of this project.

4.8 COMPARING TRUCK AND GRADE IMPACTS BASED ON MODEL OUTPUTS

4.8.1 Introduction

Planners and engineers have widely used the HCM (National Academies of Sciences Engineering and Medicine, 2022) to estimate the capacity and level of service of transportation segments, intersections, and facilities. The HCM contains specific methodologies to estimate the capacity and level of service for different interrupted and non-interrupted roadway network elements. For instance, the capacity of a basic freeway segment is estimated based on adjusted free-flow speed (FFS), which depends on the segments' geometric elements, including a base FFS, lane width, right-side shoulder width, and ramp density. In the HCM, the capacity of signalized intersections is a function of the estimated saturation flow rate, which depends on the lane width, heavy vehicles, grade, lane utilization, downstream lane blockage, sustained spillback, and other factors. For two-way stop-controlled intersections, the HCM procedure determines the capacity of movements based on the conflicting flow rate, headways, grade, and truck percentages. In general, according to the HCM procedures, the capacity of the roadways depends on several factors that are different for different facility types. The lane width, truck, and grades are critical parameters among these factors.

The HCM analysis is not sufficient for all conditions. The HCM specifies situations under which the HCM analysis is insufficient and simulation analysis is required. These situations include, for example, merging during congested conditions, active traffic and demand management (ATDM) analysis, traffic conditions when the HCM process is developed based on the simulation results as a substitute for field data collection, and when the traffic conditions are too complex to model under deterministic procedures (National Academies of Sciences Engineering and Medicine, 2022).

In addition to deterministic HCM-based tools like the Highway Capacity Software (HCS), analysts have used a number of alternative tools, including simulation analysis and other deterministic tools. These packages include Synchro, which is a deterministic tool, and SimTraffic, which is a microsimulation tool (Cubic ITS Inc, 2019; Trafficware, 2022). Examples of other utilized microscopic simulation tools include TransModeler (TransModeler, 2022), VISSIM (Verkehr In Städten – SIMulationsmodell: German; Traffic in cities - simulation model: English) (PTV AG, 2021), and AIMSUN (Advanced Interactive Microscopic Simulator for Urban and Non-urban Networks) (Aimsun, 2022). These microscopic simulation tools use microscopic traffic models like car-following, lane-changing, and gap acceptance models to simulate individual vehicle movements.

Based on 61 public and private sector responses to a survey of Florida traffic analysts conducted as part of this study and discussions in phone interviews with a selected subset of the respondents to the survey, most analysts in Florida use analytical (sometimes referred to as deterministic) HCM-based analysis tools and Synchro, in addition to the use of simulation modeling, in some cases. In general, the selection of the tools to use is made based on conditions such as closely spaced intersections, high demand-to-capacity ratios in urban areas, backups between intersections and/or interchanges, complex system configuration, express lane use, and so on. In some cases, when using simulation, the HCM analyses are performed for the initial screening of the alternatives, and simulation is used later for a more detailed analysis.

The use of different tools in the analysis raises a question about the capacity estimation in these tools considering different geometry design features. Highway geometry features have significant impacts on the capacity of the highway. However, transportation system analysts, in many cases, use the existing tools as black boxes, not understanding if and how these tools can consider the impact of the design geometry features and the need to change the default calibration parameters to account for the changing design features. This study assesses the ability of a number of deterministic analysis tools and microscopic simulation tools in considering the impacts of lane width and grade with different truck percentages on the capacity of basic freeway segments, signalized intersections, and unsignalized intersections. The study also investigates the impacts of changing the calibration parameters in microscopic simulation based on a recent study that investigated the impacts of lane width on the macroscopic and microscopic traffic measures. In addition, the study examines the impact of changing the truck composition from the default compositions to those identified in a previous study based on real-world data collection effort.

4.8.2 Review of Related HCM Procedures

The HCM procedures provide default adjustment factors that can be used to calculate the capacities of segments and intersection movements. For basic freeway segments, the HCM procedure uses a lane width of 12 ft as the base condition (National Academies of Sciences Engineering and Medicine, 2022). The capacity is calculated based on the FFS that is a function of lane width in the case of the basic freeway segment. For example, for base FFS of 65 mph, the capacity drops by 0.81% and 2.81% when decreasing the lane width from 12 ft to 11 ft and 10 ft, respectively.

The HCM signalized intersection procedure considers the capacity with lane widths of 10 ft to 12.9 ft as a base capacity. The default values in the procedure involve a 4% reduction in capacity for narrower lanes with a width of 8 ft to 10 ft and a 4% increase for wider lanes with a width of 12.9-16 ft. The HCM two-way stop-controlled intersection does not consider the impact of lane width unless there are pedestrians impacting the left and right movements. The calculation of the capacity of the left-turn movement from the major street and right-turn movement from the minor street of a two-way stop controlled intersection uses a pedestrian impedance factor, which relies on the lane width of the minor street (National Academies of Sciences Engineering and Medicine, 2022).

The HCM procedures also provide factors to account for the impacts of grades with the presence of heavy vehicles on freeways. Passenger car equivalent (PCE) factors are used to adjust the demand volume estimates to account for the influence of one heavy vehicle compared to one influence of one passenger car. The PCE factors are provided for different terrain types reflecting the overall vertical and horizontal alignment. Alternatively, the analysts can use PCE values for specific grades and heavy vehicle percentages provided by the HCM. For signalized intersection, the HCM procedure estimates the capacity of a signalized intersection based on base saturation flow rate value, adjusted using different factors that consider multiple influences, including those of the combined effect of grade and heavy vehicles. The adjustment is applicable for up to 50%

heavy vehicle percentages on a grade of -4% to +10%.

For two-way stop-controlled intersections, the HCM specifies factors to account for the impact of heavy vehicles and grades on the capacity. The calculation of a movement capacity at a two-way stop-controlled intersection requires the estimation of the critical headways and follow-up headways. The critical headway used in estimating the capacity is adjusted considering the heavy vehicles and the grade. The follow-up headway in the HCM procedure depends on the heavy vehicle but does not depend on grades.

4.8.3 Literature Review on Lane Width Impacts

Potts et al. collected data from twenty-five signalized intersections using video cameras and concluded that narrowing the lane width from 12 ft to 11 ft was not associated with a capacity drop, but a lane width reduction from 12 ft to 9.5 ft caused a capacity reduction of 4.3% and widening the lane width from 12 ft to 13 or 14 ft resulted in a 4.4% capacity increase (Potts et al., 2007). Chang et al. collected video-based data from seven intersections in China (Chang et al., 2019). The study developed a two-degree polynomial model for estimating the saturation flow rate as a function of the lane width.

Zheng et al., based on loop detector data from 440 sites in China, found that the lane width had a statistically significant effect on the capacity of three-lane urban freeways, but no significant effect on two-lane and four-lane freeways (Zheng et al., 2015). Chandra and Kumar used data collected based on video recordings from ten two-lane freeway locations to develop a regression model that shows a 12% decrease in capacity for lane width reduction from 12 ft to 11 ft and a 24% decrease for a lane decrease from 12 ft to 10 ft (Chandra & Kumar, 2003). A Federal Highway Administration (FHWA) study by Dixon et al. reported a 2.2 mph reduction in FFS for reducing the lane width of Texas freeways from 12 ft to 11 ft (Dixon et al., 2015).

Hale et al., in a FHWA project, examined the impact of freeway lane width based on an extensive data collection effort and assessed the impact of lane width on macroscopic and microscopic traffic flow measures (Hale et al., 2021). The results from this research were used for comparison purposes in this paper, and thus more details are presented here. The analysis based on macroscopic measures estimated using traffic sensor data showed that narrowing the lane width from 12 ft to 11 ft reduced capacity by 5%, 12 ft to 10 ft by 13%, and 11 ft to 10 ft by 9%. The HCM freeway procedure suggests significantly lower corresponding capacity reductions of 0.67%, 2.63%, and 1.97%, respectively. The researchers developed a new model of estimating the adjusted FFS based on lane numbers, lane width, shoulder width, posted speed limit, and segment type, which resulted in a 6.6% capacity reduction for narrowing the lane width from 12 ft to 11 ft and 15% reduction for narrowing the width from 12 ft to 10 ft. The FHWA study collected aerial videos by drone and processed the drone video with image processing to produce vehicle trajectory data. They proposed modifying the parameters of the Wiedemann 74 car-following model in VISSIM and the reaction time component of the Gipps car-following model in AIMSUN to analyze the effect of narrowing lanes on freeways based on the vehicle trajectory data extracted from the field data and also the identified lane width impact on capacity discussed earlier (Hale et al., 2021). Although VISSIM uses Wiedemann 99 car-following model for freeways by default, they found that the Wiedemann

74 model performed better for reduced speed traffic conditions by using the method recommended by Rakha & Gao for Wiedemann 74 model calibration (Rakha & Gao, 2010).

The reviews of the literature presented in this section indicate that there is a wide variation in the reported impacts of lane width in the literature. The literature reported reductions in freeway capacity for changing the lane widths from 12 ft to 11 ft ranging between 0.67% and 12%; and for changing the lane width from 12 ft to 10 ft between 2.63% and 24%.

4.8.4 Literature Review on Heavy Vehicle and Grade Impacts

The review presented in this section also indicates that the reviewed studies vary in their reporting of the impacts of trucks and grades on capacity. Yuksel et al. used dual loop detector data and found that for level terrain, the PCE values are about 1.5, 2.25, and 4.0 on a basic freeway segment for single unit truck (SUT) (length 20-35 ft), medium size truck (length 35-60 ft), and large size truck (length 60-120 ft), respectively, while the HCM recommends a PCE value of 2.0 for all heavy vehicle types on level terrain (Yuksel et al., 2022). Washburn and Cruz-Casas, based on simulation analysis calibrated using video data from six signalized intersection locations, suggested PCE values of 1.8, 2.2, and 2.8 for small (length 30 ft), medium (length 45 ft), and large trucks (length 65 ft) for the level terrain (Washburn & Cruz-Casas, 2010). Webster and Elefteriadou observed that the PCE value increased with traffic flow, FFS, and grade and decreased with an increase in truck percentage and lane numbers based on freeway simulation analysis (Webster & Elefteriadou, 1999).

Lahiri and Hadi, based on microscopic simulation runs using two widely used simulation tools, confirmed that the impacts of heavy vehicles on congested freeway sections capacity are highly dependent on the coded heavy vehicle attributes. The results were also compared with the impacts suggested in the Highway Capacity Manual 2000 (HCM 2000) and previous work on the subject (Lahiri & Hadi, 2007).

Based on simulation analysis, Washburn and Ozkul found that increasing grade percentage, length of grade, free flow speed, flow rate, and proportion of trucks, and decreasing lane numbers increased the PCE values for freeway segments (Washburn & Ozkul, 2013). They reported PCE values from 1.18 to 3.42 for single unit truck (SUT), 1.21 to 3.57 for semi-trailer trucks, and 1.32 to 4.08 for semi-double trailers, with truck percentages from 2-20% at grade 0% to 6%. The latest edition of HCM recommended PCE value of 1.97 to 9.19 for a truck mix of 30% SUT and 70% tractor-trailer (TT), 1.93 to 12.15 for a truck mix of 50% SUT and 50% TT, and 1.83 to 11.81 for 70% SUT and 30% TT for freeways and multilane highways with 2% to 25% or higher trucks on the grade of -2% to 6%.

Skabardonis et al. assessed the effect of trucks and grades on the saturation flow rates of signalized intersections using field data to develop and calibrate the microscopic simulation model (Skabardonis et al., 2014). For 10% truck on -4% to 10% grade, they found PCE values of 1.24 to 7.06 for a mix of 75% SUT and 25% semi-trailer, and 1.37 to 7.21 for 50% SUT and 50% semi-trailer. The latest edition of HCM does not consider the impact of truck composition on the PCE values.

Based on microsimulation analysis, List et al. found that the capacity of automobiles on one-mile length segments with 5% grade dropped from 2,000 vehicle per hour per lane (vphpl) to 1,500 vphpl with 5% trucks in the traffic stream (List et al., 2015). The researchers developed kinematic models for predicting passenger car, SUT, and TT flow rates using the outputs of the microsimulation software, which showed that the truck percentages, traffic flow rate, travel distance, and grade were the essential factor in calculating the impacts of trucks on capacity.

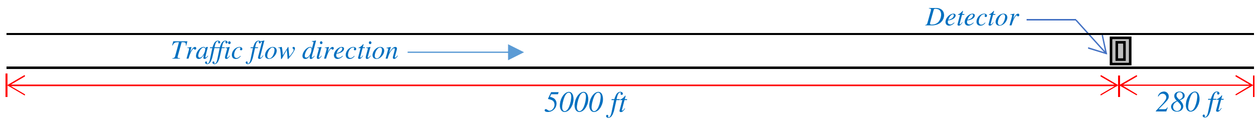
Moridpour et al. studied the effect of heavy vehicles on freeway operations in terms of average travel time and the number of lane-changing maneuvers on the freeway using a microscopic traffic simulation package (Moridpour et al., 2015). Zhou et al. estimated the truck PCEs based on a microscopic simulation model calibrated for Nebraska empirical conditions, including truck length distribution (Zhou et al., 2019). They found that the sixth edition of the HCM underestimates the effects of trucks on four-lane level freeway segments that experience high truck percentages. Al-Kaisy and Jung investigated the impact of heavy vehicles and grades on freeway operation through a traffic simulation model calibrated based on field data (Al-Kaisy & Jung, 2004). They estimated the PCE factor based on the queue discharge flow. Under free-flow conditions, the effect of heavy vehicles on traffic flow increases with the increase of grade, and the influence of grade on PCE factors is more significant with longer grade lengths and smaller percentages of heavy vehicles.

4.8.5 Methodology

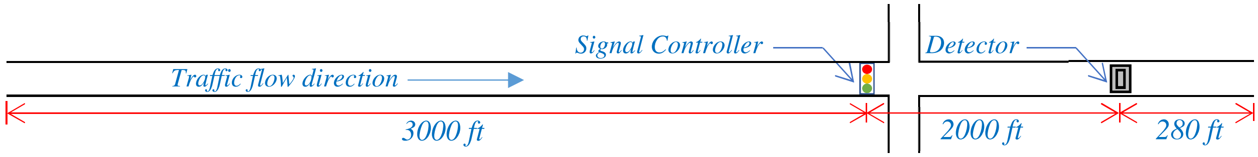
This section describes the methodology used in this study to assess and compare the consideration of lane width, truck presence, and grades on capacity in analysis tools and the impacts of changing some of the inputs parameters on the results.

4.8.5.1 Modeled Roadway Segments

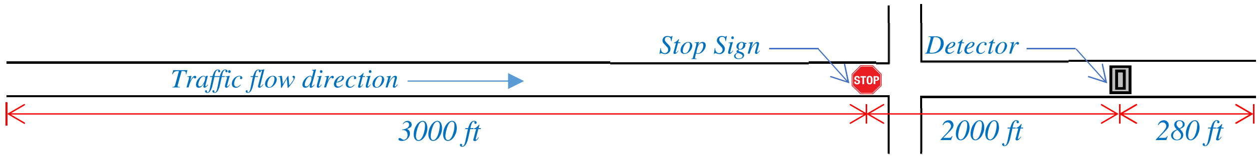
Figure 4-1 shows a simplified diagram of the three single-lane hypothetical roadway segments modeled in the examined tools in this study. The FFS was set to 65 mph for the freeway segment and 45 mph for the segments with signalized and unsignalized intersections. The signal control was set as a fixed timed control with 120 seconds green time with a total cycle length of 180 seconds. The traffic control devices (signal controller and stop sign) were placed at 3,000 ft from the beginning of the segments. The capacity was assessed based on traffic volumes collected from virtual detectors placed downstream of the link for which the capacity was estimated.



(a) Basic Freeway Segment



(b) Signalized Intersection Segment



(c) Unsignalized Intersection Segment

Figure 4-1 Modeled roadway segments

4.8.5.2 Utilized Tools

This study compared the capacity impacts using three HCM-based analytical tools (sometimes referred to as deterministic tools), which are the Highway Capacity Software (HCS) Version 7.8.5 (McTrans Center, 2019), Synchro Version 11.0 (Trafficware, 2022), and an analytical tool that is included with the TransModeler simulation package (TransModeler, 2022) for analyzing signalized and unsignalized intersections based on the HCM procedures (this third tool is referred to as TM-Analytical in this document). The comparison also includes examining the capacity as assessed by three microscopic simulation tools, which are SimTraffic Version 11.0 (Trafficware, 2022), TransModeler Version 6.0 (TransModeler, 2022), and VISSIM Version 2021 (PTV AG, 2021). The models in the simulation tools were calibrated to produce base capacity values (with 12 ft lane, zero grade, and zero truck proportion) close to those estimated using the HCM procedure.

4.8.6 Analyzing the Impact of Lane Width and Truck and Grade on Capacity

After calibrating the base models, this study simulated different scenarios to quantify the impacts of lane width on capacity, referred to as LW in the remaining of this paper, and the combined effect of the truck percentage and grade on capacity, referred to as TG in the remaining of this paper. To assess the impact of the LW, the study varied the LW between 9 ft and 12 ft. To assess the impact of TG, two truck percentages (0% and 10%) were incorporated in the traffic stream in models with two upgrades (0% and 6%). For each modeled scenario in microscopic simulation, 20 runs were conducted to account for the stochasticity in the models.

As stated earlier, an FHWA project examined the impacts of LW on the capacity of freeways based on macroscopic measures using sensor data and microscopic measures using drone data (Hale et al., 2021). The study provided recommendations for changing the Wiedemann's car-following model parameters in VISSIM to account for LW impacts. This current study conducted additional VISSIM analysis using three sets of parameters based on the recommendations in the FHWA study. The three sets of parameters are:

- Recommendation based on general analysis and observations to increase the values of the three basic car following parameters in VISSIM (CC0, CC1, and CC2) by 10% for each one-foot lane width reduction
- Values of the three basic calibration parameters estimated based on vehicle trajectories obtained using drone video data collected in Honolulu, HI, for lane widths 11 ft and 10 ft
- Values of the three basic calibration parameters based on vehicle trajectories obtained from drone video data collected in San Antonio, TX, for lane widths 12 ft and 11 ft

The three parameters varied in the FHWA report (Hale et al., 2021) are the AX (also referred to in the literature as CC0), which is the average distance between stopped vehicles in ft; and the BX_{add} and $BX_{mult,}$ (also referred to as CC1 and CC2), which are the additive and multiplicative parts of safety distance, respectively, which define the safe distance of vehicles during car-following (PTV AG, 2021).

The default composition of trucks in terms of the distribution of the type of the modeled trucks are different in different tools. This can contribute in parts to the difference in the impacts of TG on the capacity. In many cases, modelers do not vary the default distributions of trucks in the tools, even if this is possible. This raises the question of the effect of changing the truck composition on the resulting impacts of TG on capacity. The HCM freeway procedure allows the selection between specific percentages of two types of trucks (SUT and TT). However, the HCM procedures of urban street segments and signalized intersections consider the trucks as any vehicle with more than four wheels (FHWA class 5-13). The default distribution of heavy vehicles in SimTraffic consists of one bus (length 40 ft) and four truck types, which are single unit trucks (length 35 ft), single TT trucks (length 53 ft or higher), shorter single TT trucks (length 53 ft), and truck with two-trailers, length (64 ft) (ODOT, 2022). The default composition of the heavy vehicle is 60% 10%, 5%, and 5%, in addition to 20% buses. VISSIM default truck is one type of truck, referred to as HGV EU, which is the European heavy ground vehicle (length 33.5 ft), which is equivalent to FHWA Class 5-6 (AECOM, 2020). The heavy vehicle fleet in the TransModeler consists of three types of trucks (pickup truck/utility vehicle like SUV, single-unit truck, and trailer truck) and two types of buses (regular bus and articulated transit bus) (TransModeler, 2020). The user can modify the default compositions of trucks in SimTraffic, VISSIM, and TransModeler.

Additional analysis was conducted in this study to quantify the impact on the capacities of changing the truck composition from the default in the tested simulation tools. In addition to modeling the trucks with the default composition, an additional composition was used as input to VISSIM. This composition was reported in a study in Florida as included in the HCM (National Academies of Sciences Engineering and Medicine, 2022; Washburn & Ozkul, 2013). The Florida truck composition was identified based on weigh-in-motion data collected by the above-mentioned study and is listed below:

- FHWA Class 5: Two-axle, six-tire single unit trucks (freeway 28.6%, multilane highway 33.6%)
- FHWA Class 6: Three-axle single-unit trucks (freeway 6.6%, multilane highway 16.7%)
- FHWA Class 7: Four or more axle single-unit trucks (freeway 1.3%, multilane highway 3.5%)
- FHWA Class 8: Four or fewer axle single-trailer trucks (freeway 11.2%, multilane highway 10.3%)
- FHWA Class 9: Five-axle single-trailer trucks (freeway 48.3%, multilane highway 34.9%)
- FHWA Class 10: Six or more axle single-trailer trucks (freeway 0.6%, multilane highway 0.5%)
- FHWA Class 11: Five or fewer axle multi-trailer trucks (freeway 2.1%, multilane highway 0.3%)
- FHWA Class 12: Six-axle multi-trailer trucks (freeway 0.9%, multilane highway 0.2%)
- FHWA Class 13: Seven or more axle multi-trailer trucks (freeway 0.3%, multilane highway 0.1%)

4.8.7 Results and Discussion

This section discusses the results of analyzing the impacts of LW and TG on the capacity of basic freeway segments, signalized intersections, and unsignalized intersections.

4.8.7.1 Impact of LW on Capacity

Basic Freeways

Table 4-4 shows a comparison of the LW impact on the capacity of the basic freeway segment as assessed using the HCS, TransModeler, and VISSIM, in addition to those suggested in the previously mentioned FHWA report (Hale et al., 2021). The results from the HCS revealed that lane width reduction from 12 ft to 11 ft and from 12 to 10 ft resulted in a drop in capacity of 0.81% and 2.81%, respectively. The FHWA study indicated much higher impacts of LW on capacity compared to the HCM. VISSIM showed negligible impacts of LW on capacity, confirming that when using this tool, the LW impact has to be accounted for by the user by modifying the car-following model parameters in the tool. On the other hand, TransModeler showed similar impacts of LW on capacity as calculated based on the HCM, indicating that the parameters of the car following the model of the tool has been adjusted internally by the tool developer to consider the LW impact on freeway segments.

Table 4-4 Comparison of capacity impact of lane width change

Lane Width, ft	Freeway Capacity (deviation from the base scenario of 12 ft lane width, %)						
	HCS, pcphpl (%)	Synchro, vphpl (%)	TM-Analytical, vphpl (%)	FHWA Report Values, vphpl (%)	SimTraffic, vphpl (%)	TransModeler, vphpl (%)	VISSIM, vphpl (%)
Basic Freeway							
10	2284 (-2.81%)	N/A	N/A	1547 (-13.14%)	N/A	2310 (-2.57%)	2296 (-0.17%)
11	2331 (-0.81%)	N/A	N/A	1695 (-4.83%)	N/A	2358 (-0.55%)	2296 (-0.17%)
12	2350 (0%)	N/A	N/A	1781 (0%)	N/A	2371 (0%)	2300 (0%)
13	N/A	N/A	N/A	(%)	N/A	2377 (0.25%)	2306 (0.26%)
Signalized Intersection Approach							
9	1131 (-3.99%)	1100 (-4.01%)	1158 (-3.98%)	N/A	1274 (-6.87%)	1317 (-0.23%)	1324 (0%)
10	1178 (0%)	1146 (0%)	1206 (0%)	N/A	1308 (-4.39%)	1318 (-0.15%)	1324 (0%)
11	1178 (0%)	1146 (0%)	1206 (0%)	N/A	1340 (-2.05%)	1319 (-0.08%)	1324 (0%)
12	1178 (0%)	1146 (0%)	1206 (0%)	N/A	1368 (0%)	1320 (0%)	1324 (0%)
13	1225 (3.99%)	1192 (4.01%)	1255 (4.06%)	N/A	1396 (2.05%)	1319 (-0.08%)	1326 (0.15%)
Through Movement of Minor (Controlled) Approach at Two-Way Stop Controlled Intersection							
9	893 (0%)	891 (0%)	893 (0%)	N/A	944 (-1.67%)	557 (-0.18%)	536 (0%)
10	893 (0%)	891 (0%)	893 (0%)	N/A	948 (-1.25%)	557 (-0.18%)	536 (0%)
11	893 (0%)	891 (0%)	893 (0%)	N/A	956 (-0.42%)	556 (-0.36%)	536 (0%)
12	893 (0%)	891 (0%)	893 (0%)	N/A	960 (0%)	558 (0%)	536 (0%)
13	893 (0%)	891 (0%)	893 (0%)	N/A	968 (0.83%)	557 (-0.18%)	536 (0%)

Note: N/A = Not applicable because these tools do not model freeways

Signalized Intersections

Table 4-4 shows the LW impact on the capacity of signalized intersections. Both VISSIM and TransModeler showed insignificant variation in capacity with the change in LW at the signalized intersection. As stated earlier, this was also the case with VISSIM for freeways, but TransModeler was able to account for the change in lane width for freeways. The three analytical tools (HCS, Synchro, and TM-Analytica) that apply the signalized intersection HCM procedure showed that the capacity remains unchanged when increasing the lane width from 10 ft to 12 ft. However, the capacity dropped by 4.18% when the lane width narrowed to 9 ft and increased by 4.14% when the lane width increased to 13 ft. The change in the capacity in SimTraffic is higher than the change in capacity in the three analytical tools, showing a 7.38% decrease in capacity for 12 ft to 9 ft LW reduction compared to 4.15% in the analytical tools.

Two-Way Stop Controlled Intersection

Table 4-4 shows the capacity at unsignalized intersections with different lane widths. The results in the table indicate that the results from all analytical and simulation tools do not show an impact of LW on the capacity of the through movement on minor (controller) approaches, except that the results from SimTraffic show that there is an increase in capacity with increasing LW, reaching a 2.54% increase, when the lane width increased from 9 ft to 13 ft.

Modifying Simulation Model Parameters According to FHWA Report Recommendation

The next step was to examine the results of calibrating VISSIM to simulate the impact of LW reduction on freeway capacity based on the FHWA report recommendation (Hale et al., 2021). As stated earlier, this study compared the use of three different sets of car-following parameters based on that study. Table 4-5 shows that the utilization of a 10% increase in the values of the three basic car following parameter for each one-foot lane width reduction resulted in a capacity reduction of 5.1% and 9.9%, with changing LW from 12 ft to 11 ft and from 12 ft to 10 ft, respectively. These results are close to the recommended values for the reduction in capacity in the FHWA report but significantly higher than the HCM values, as shown in Table 1. Using parameters derived based on vehicle trajectories from Hawaii and Texas resulted in even a higher reduction of 11.3 % when decreasing the lane width from 12 ft to 11 ft based on Texas data and 8% when decreasing the lane width from 11 ft to 10 ft based on Hawaii data (Hale et al., 2021).

Table 4-5 Capacity reduction when using Vissim car-following parameters from the FHWA Study

Parameter Set	Lane width (ft)	AX (ft)	BX_{add}	BX_{mult}	Capacity (vphpl)	Capacity Change (%) per Feet Lane Width Reduction
10% increase in parameter values for each one-ft lane width reduction	12	6.5617	2	3	2230	0.0%
	11	7.2178	2.2	3.3	2116	-5.1%
	10	7.8740	2.4	3.6	2010	-5.0%
Data collected from Honolulu, HI, for lane widths 11 ft and 10 ft	11	7.0310	1.434	4.565	2150	0.0%
	10	7.0310	1.865	5.046	1978	-8.0%
Data collected from San Antonio, TX, for lane widths 12 ft and 11 ft	12	18.13	1.476	3.831	1978	0.0%
	11	27.339	1.542	4.445	1754	-11.3%

4.8.7.2 Impact of Truck and Grade on the Capacity of Roadways

Basic Freeways

Table 4-6 indicates that the incorporation of 10% truck in the traffic stream with 0% grade resulted in approximately 10%, 8%, and 1% reduction in the capacity as estimated by the HCS, VISSIM, and TransModeler, respectively. This indicates that VISSIM with the default truck parameters on zero grade produced a close drop in uninterrupted facility capacity to that of the HCM. With 6% grade, 10% trucks in the traffic stream resulted in an 18% drop in capacity according to the HCM but 26% according to VISSIM. However, TransModeler does not seem to show a significant reduction in capacity, indicating it cannot adequately consider the impact of trucks on the capacity of uninterrupted facilities.

Table 4-6 Capacity comparison of the basic freeway section with default truck composition

Scenarios	Capacity (deviation from base scenario of 0% truck and 0% grade, %)					
	HCS, pcphpl (%)	Synchro, vphpl (%)	TM-Analytical, vphpl (%)	SimTraffic, vphpl (%)	TransModeler, vphpl (%)	VISSIM, vphpl (%)
Basic Freeway						
0% Truck on 0% Grade	2350 (0%)	N/A	N/A	N/A	2285 (0%)	2430 (0%)
0% Truck on 6% Grade	2350 (0%)	N/A	N/A	N/A	2284 (-0.04%)	2324 (-4.36%)
10% Truck on 0% Grade	2113 (-10.09%)	N/A	N/A	N/A	2265 (-0.88%)	2242 (-7.74%)
10% Truck on 6% Grade	1935 (-17.66%)	N/A	N/A	N/A	2270 (-0.66%)	1806 (-25.68%)
Signalized Intersection Approach						
0% Truck on 0% Grade	1206 (0%)	1173 (0%)	1235 (0%)	1406 (0%)	1341 (0%)	1338 (0%)
0% Truck on 6% Grade	1072 (-11.11%)	1043 (-11.08%)	1097 (-11.17%)	1378 (-1.99%)	1339 (-0.15%)	1296 (-3.14%)
10% Truck on 0% Grade	1112 (-7.79%)	1082 (-7.76%)	1139 (-7.77%)	1310 (-6.83%)	1283 (-4.33%)	1290 (-3.59%)
10% Truck on 6% Grade	977 (-18.99%)	951 (-18.93%)	1001 (-18.95%)	1282 (-8.82%)	1188 (-11.41%)	1196 (-10.61%)
Through Movement of Minor (Controlled) Approach at Two Way Stop Controlled Intersection with **10 vphpl** on the Major Street Approach						
0% Truck on 0% Grade	888 (0%)	888 (0%)	889 (0%)	972 (0%)	764 (0%)	540 (0%)
0% Truck on 6% Grade	885 (-0.34%)	884 (-0.45%)	889 (0%)	964 (-0.82%)	756 (-1.05%)	532 (-1.48%)
10% Truck on 0% Grade	868 (-2.25%)	868 (-2.25%)	869 (-2.25%)	916 (-5.76%)	756 (-1.05%)	516 (-4.44%)
10% Truck on 6% Grade	865 (-2.59%)	865 (-2.59%)	869 (-2.25%)	912 (-6.17%)	740 (-3.14%)	512 (-5.19%)
Through Movement of Minor (Controlled) Approach at Two Way Stop Controlled Intersection **with 120 vphp**l on the Major Street Approach						
0% Truck on 0% Grade	767 (0%)	766 (0%)	774 (0%)	900 (0%)	680 (0%)	540 (0%)
0% Truck on 6% Grade	735 (-4.17%)	734 (-4.18%)	774 (0%)	896 (-0.44%)	669 (-1.62%)	536 (-0.74%)
10% Truck on 0% Grade	748 (-2.48%)	748 (-2.35%)	755 (-2.45%)	844 (-6.22%)	666 (-2.06%)	520 (-3.70%)
10% Truck on 6% Grade	717 (-6.52)	717 (-6.4%)	755 (-2.45%)	840 (-6.67%)	656 (-3.53%)	512(-5.19%)

Note: N/A = Not applicable because these tools do not model freeways

Signalized Intersections

Table 4-6 presents the impacts of trucks and grades on the capacity at signalized intersections. Again, the three HCM-based analytical tools (HCS, Synchro, and TM-Analytical) produced about the same drops in capacity (7.8% with 10% trucks on 0% grade and 19% with 10% trucks on 6% grade). SimTraffic results show much lower impacts of about 2% capacity drop with 10% trucks on 0% grade and about a 9% capacity drop with 10% trucks on 6% grade. These values were about 3% and 11% when using VISSIM and about 0.2% and 11.4% when using TransModeler. This indicates that at signalized intersections, the three microsimulation tools with the default truck compositions produced a lower drop in capacity compared to the HCM-based analytical tools.

Two-Way Stop Controlled Intersections

Table 4-6 indicates that the results from the HCM-based analytical tools (HCS, Synchro, and TM-Analytical) show a similar impact of grade and truck on the capacity of the through movement of the minor (controlled) approach at two-way stop-controlled intersection. When the opposing traffic was 10 vphpl and 120 vphpl, the drop in capacity was about 2.5% and 6.5% with introducing 10% truck and 6% grade in the model. This indicates that the HCM procedure estimates higher percentage drop in capacity due to TG with higher opposing traffic volumes. The results from SimTraffic, Vissim, and TransModeler exhibited 6.17%, 4.87%, and 5.19% drops in capacity with 10% trucks in traffic at 6% grade and 10 vphpl opposing traffic. Unlike, the HCM-based procedures, the results from the tested simulation tools did not indicate a significantly higher percentage reduction in capacity with increasing the opposing traffic volume on the major street.

Impact of Truck Composition

The results presented above are obtained using the default truck composition in the tested tools. Table 4-7 shows the results when the truck composition in VISSIM was modified to correspond to the composition reported in a Florida study (referred to as Reported Florida Composition in Table 4). As stated earlier, for freeway segments, utilizing the default composition in VISSIM resulted in a 25.68% reduction in capacity with 10% truck on 6% grade compared to a 17.66% drop according to the HCM. Using the Reported Florida Composition in VISSIM resulted in 19.51% reductions in capacity. This indicates that the default composition in VISSIM overestimates the impact of trucks on upgrades for freeway segments, and the use of a composition based on a local study produced values closer to the impacts according to the HCM. For signalized intersections, the HCM estimates of the drop in capacity were 7.8% with 10% trucks on 0% grade and 19% with 10% trucks on 6% grade. Table 4-7 shows similar capacity reductions when using VISSIM with the default truck composition and reported Florida composition (10.61% and 8.07% capacity reduction with 10% truck on 6% grade for the two compositions, respectively. These impacts are lower than those produced based on the HCM procedure shown in Table 3 (about 19%).

Table 4-7 Capacity with different truck composition input to Vissim

Scenarios	Capacity (deviation from base scenario, %)	
	VISSIM Default, vphpl (%)	Reported Florida Composition, vphpl (%)
Basic Freeway		
0% Truck on 0% Grade	2430 (0%)	2430 (0%)
0% Truck on 6% Grade	2324 (-4.36%)	2324 (-4.36%)
10% Truck on 0% Grade	2242 (-7.74%)	2238 (-7.9%)
10% Truck on 6% Grade	1806 (-25.68%)	1956 (-19.51%)
Signalized Intersection		
0% Truck on 0% Grade	1338 (0%)	1338 (0%)
0% Truck on 6% Grade	1296 (-3.14%)	1296 (-3.14%)
10% Truck on 0% Grade	1290 (-3.59%)	1286 (-3.89%)
10% Truck on 6% Grade	1196 (-10.61%)	1230 (-8.07%)

4.8.8 Conclusions

This study examined the ability of HCM-based deterministic analysis tools and microscopic simulation tools to assess the impacts of lane width and upgrade with different truck percentages on the capacity of basic freeway segments, signalized intersections, and unsignalized intersections. The study also investigated the impacts of changing the parameters of microscopic simulation models on the assessment of the impacts of these design features. The results indicated that the current versions of these tools do not consistently consider the impact of the investigated design features on highway capacity. The results indicate different changes in capacity due to the changes in geometry and truck percentages. The results from some tools do not show impacts of specific geometry features without changing the default calibration parameters for the modeled segments. In another case, a tool was able to model the impacts of a feature on capacity only on interrupted facilities or only for uninterrupted facilities.

A recent FHWA report suggested that the HCM may underestimate the impact of lane width on capacity. This study calibrated a microscopic simulation model using calibration parameters that were suggested in that report based on macroscopic measurements of capacity and microscopic measurements of traffic flow parameters derived using vehicle trajectories. The results indicated that the analysts need to change the calibration parameters in the utilized tools to produce the expected drop in capacity with narrow lanes.

It was also found that different analytical and simulation tools have different default truck type compositions. For freeways, it was found that using the default truck composition in one of the microsimulation tools that is based on a typical truck composition in the European Union overestimates the capacity impact of trucks on upgrades and that the use of a produced composition based on a Florida study produced values closer to the impacts according to the HCM-based tools. For signalized intersection approaches, the HCM-based tool estimates of the drop in capacity due the combined truck and upgrade impact were higher than the drop in capacity assessed according to simulation models with and without changing the composition of the trucks, although changing the truck composition to that based on a Florida study indicates a lower assessed impact.

For two-way stop-controlled intersections, this study found that most tools did not show an impact of lane width on capacity of the through movement on the minor (controller) approaches. The results indicate higher impacts of trucks and grades on the capacity of this movement in simulation tools compared to HCM-based tools for lower opposing traffic flow on the major street, but a similar impact with a higher opposing flow. It is interesting that the results showed that the percentage change in capacity due to trucks and grade increases with the increase in the opposing flow according to HCM-based tools but not according to simulation tools.

CHAPTER 5: PROVIDING DIRECTION ON THE APPLICATION OF MULTIRESOLUTION MODELING

5.1 INTRODUCTION

Based on level of details, traffic simulation models are categorized into three different resolution levels: macroscopic, microscopic, and mesoscopic. The fidelity of data, network, and other modeling attributes increases as the modeler moves from macroscopic to microscopic models. Macroscopic models use macroscopic traffic models, parameters, and measures such as traffic flow, average speed, and density to model traffic operations. Microscopic models simulate individual vehicle dynamics and driver's behavior and utilize microscopic models such as car following, lane changing, and gap acceptance. Although macroscopic models render faster processing time and are easier to develop and calibrate, microscopic simulation models can be more accurate and precise, if well calibrated and validated. On the other hand, mesoscopic models combine properties of both microscopic and macroscopic models. In most cases, they use aggregated speed-density (macroscopic) relationships but depict the motions of individual vehicles (microscopic), although some mesoscopic models use low fidelity car following and lane selection models. Mesoscopic simulation models provide less fidelity than microsimulation tools but are more computationally efficient making them ideal to use in the iterative process required for dynamic traffic assignment. Particularly for large networks. Depending on network size and the types of analyses required, all types of models are potentially valuable for transportation analysis. A multiresolution modeling (MRM) framework that combines different modeling revolution has found significant interest in recent years to answer questions related to traffic operations and advanced strategies.

This chapter reports on the results of Task 4 of the project, aiming to provide direction on the application of MRM. This effort will build on recent national effort funded by the FHWA that provided a review of the state of practice, guidance, and case studies for the use of MRM (Hadi et al., 2022a, 2022b; Zhou et al., 2021). The principal investigator (PI) for this project was also a PI for the FHWA project. It is recommended that the FDOT team that is developing and maintaining the FDOT Traffic Analysis Handbook (TAH) review the FHWA project deliverables and incorporate information from the deliverables in the FDOT TAH. This chapter includes the followings:

- Recommend Guidance based on a recently completed FHWA project on MRM
- Develop methods for integrating crowdsourced data from a third-party data vendor in the process of estimating the origin-destination matrix estimation (ODME) process required for the MRM for the modeled scenario(s)
- Assess the use of crowdsourced data platform obtained from third-party vendors to estimate segment level daily and hourly volumes.

5.2 GUIDANCE BASED ON RECENTLY COMPLETED PROJECT

As stated earlier, the FHWA and the Traffic Analysis and Simulation Pooled Fund Study sponsored a research project on multiresolution modeling (MRM). The project provides guidance that summarizes MRM terminology and definitions, a methodology for MRM analysis, and three case studies of applying MRM (Hadi et al., 2022a, 2022b). The MRM methodology in the guide extends the methodology provided for simulation analysis in FHWA's Traffic Analysis Toolbox Volume Ⅲ: Guidelines for Applying Traffic Microsimulation Modeling Software (Wunderlich et al., 2019). The following are the steps that are addressed in the guidance. As stated earlier, these steps should be reviewed by the FDOT TAH development and maintenance team for use in updating the TAH.

MRM Scoping and Planning: This includes making decisions regarding the MRM utilization and approach based on the needs and objectives. It involves specifying and defining performance measures to be estimated using different resolutions of MRM, determining additional data requirements for the use of MRM, identifying the geographic and temporal scope for each resolution, identifying the analysis approach for each resolution level, and resource allocation.

Data Collection and Analysis: This step considers that MRM requires additional data collection and processing activities. It should be mentioned that the main objective of the MRM task conducted as part of the FDOT project is to investigate the use of data from multiple sources to support the MRM.

Base Model Development and Error Checking: The methodology then addresses the additional effort required for MRM model development including interfacing MRM tools, disaggregating zones, and modifying connectors, origin-destination (O-D) demand estimation, signal control modeling, advanced technology modeling, and multiscenario analysis.

Model Calibration and Convergence: This involves the steps required for MRM calibration. These steps include bottleneck identification, traffic flow model calibration for different resolutions, and travel demand calibration.

Alternatives Analysis: This step includes accounting for model stochasticity, estimating future-year demands, estimating, and optimizing signal timing, and conducting sensitivity analysis to account for uncertainty in model inputs.

The guidance also provides recommendations to improve the organizational and technical capabilities of the agencies to increase their MRM analysis capabilities in various dimensions including the business processes, performance estimation, data collection and management, development of standard operating guidance, tool utilization, workforce development, collaboration, and culture.

The FHWA guidance referenced previous FDOT projects by Hadi et al. that developed MRM tool assessment criteria to enable the comparison of various modeling tools to ensure they meet the needs of a specific project (Hadi et al., 2012, 2016). The criteria for tool assessment cover general hardware and software, shortest path and path choice modeling, traffic flow modeling, network geometry modeling, network demand modeling, transit modeling, and calibration/validation and convergence assurance support. Additional criteria were developed for specific applications such as managed lane, work zone, and advanced traffic management strategy modeling.

A critical aspect of MRM is to understand how different performance measures are calculated by different tools at different resolution levels. Measures such as travel time, delays, stops, queues, and density have the same name in different tools but are defined and calculated differently.

An important aspect that was introduced an emphasized in the FHWA guidance is to ensure consistency between different levels of modeling by applying feedback from higher resolution (macroscopic) models to lower resolution (microscopic) models. The first measure to adjust for consistency between different resolutions is capacity or throughput at the bottleneck locations between the macroscopic, mesoscopic, and microscopic models. Capacity is an input to macroscopic models and some mesoscopic models. However, it is an output in some mesoscopic models and all microscopic models and assessed based on microscopic traffic flow parameters. The analyst should fine-tune the parameters of macroscopic, mesoscopic, and microscopic model parameters to ensure the consistency of the capacity between different models. In a feedback loop, the analyst can use the calibrated capacities at the lower level (higher resolution microscopic) models to refine the capacities in the upper-level models. The next step is to the parameters of the models with different resolutions of analysis to ensure travel time/delay performance consistency between different models, given the realized demands and capacities.

5.2.1 Project Planning and Scoping

If MRM is considered for use, the simulation projects need additional effort during the planning and scoping stage to identify the needs and additional data and activities required for MRM. MRM can increase the need for integration of models that are possibly developed by different entities. It can also increase the spatial limits of the modeling and data needs. The analyst should examine the project objectives to determine the need for MRM. MRM is suited to problems and alternative solutions that impact strategic traveler behaviors such as shifts in routes, destinations, modes, times of travel, and even land use. In particular, currently available tools to support MRM provide better assignment of traffic to alternative routes using simulation using DTA. It is also possible to address strategic behavior changes by extending the capabilities of tools or integrating with discrete choice models.

An important aspect of MRM is to identify the geographic and temporal limits for each resolution including the analysis study area, time periods, time horizon, modes, and facilities modeled in each resolution. This identification should be based on analysis of system performance, alternative routes, and the expected and extent of the impacts. It is important to examine the level of details required in modeling each geographic area within the modeled network. It is also important to consider the availability of data in space and time at the required level for each resolution.

An important consideration when setting the scope and selecting the modeling approach is to determine the available and required resources and budget for the model. MRM may require additional budget and capabilities that may not be available to the modeling team. The resource limitations may also require the agency to adjust its scope to model as much of the impacted network as possible, considering the resource constraints. In this case, the analyst should set temporal and spatial scopes of the models at different resolutions by considering and prioritizing those areas and time periods expected to be the most impacted by the proposed improvement strategies.

At the planning stage, the analyst also selects the combinations of tools for the project. Hadi et al. recommended the development and use of tool assessment criteria as part of a supporting environment for multiresolution analysis (Hadi et al., 2011, 2016). These criteria allow the comparison of various modeling tools to ensure that they meet the needs of a specific project. The criteria for tool assessment covers general hardware and software, shortest path and path choice modeling, traffic flow modeling, network geometry modeling, network demand modeling, transit modeling, and calibration/validation and convergence assurance support. Hadi et al. also developed additional criteria for specific applications such as managed lane, work zone, and advanced traffic management strategy modeling (Hadi et al., 2011, 2016).

5.2.2 Data Requirements and Availability

Depending on the modeling scope and configuration, MRM may require additional traffic, network, control, and management data for a much larger size network. It is important to consider data requirement and availability in the initial planning and scoping of the project. If the additional data required for MRM is not available and or feasible to collect, analysts should reconsider the use of MRM.

In some specific cases, the spatial and temporal scopes of the mesoscopic and microscopic model components of the MRM are the same. In these cases, the mesoscopic model is used for DTA while the microscopic model is used to assess the performance. In this case, the data required for microsimulation modeling is sufficient for MRM. An extra data cost in this case would be the acquisition of O-D measurements to help in refining the O-D matrices, if a decision is made to acquire such data in the scoping stage, However, in many other projects the macroscopic, mesoscopic, and microscopic modeling geographic and temporal scopes are different. In particular, the MRM in these cases require the modeling of significantly larger size network compared to the microscopic model thus increasing the data requirements compared to just using microscopic simulation.

The input data requirement is different for different analysis levels and resolutions and also different depending on the specific tool. In general, simulation models require road geometry, traffic control, demand, travel times, and other measures of performance required for calibration. However, the required details of these items increased for higher resolution models.
Depending on the tool and level of analysis, the analysts can represent the demands (usually at 15-minute to 30-minute intervals) as entry volumes, turning movement volumes, paths from origin to destination, O-D tables, and individual vehicle trips. Models that are used for static and dynamic traffic assignment tools utilize O-D matrices as inputs.

5.2.3 Signal Control Treatment

Signal control data are usually required at least for the mesoscopic and microscopic resolutions of MRM. The synthesis of signal control is a feature available in some existing DTA tools.

Experience shows that inputting real-world signal control data in the mesoscopic simulation model-based DTA produces much better results than requesting the synthesis of signal timing as part of DTA modeling (Hadi et al., 2014). When converting networks from demand forecasting models to higher resolution models, the analysts must add the signal timing details. For existing conditions, analysts can obtain the information from the signal control agencies. Supporting tools could be helpful in automatically converting the signal timing into formats accepted by the detailed modeling tools and archiving these plans for future use. For example, the San Francisco Transportation Authority developed a Python-based signal importing function as part of the DTA Anyway effort (Hadi et al., 2014). When modeling future years and/or improvement alternative scenarios that change the demands or the network, there is a need for the calculation of new signal timing plans. Tools will be required to optimize the signal control for future conditions.

5.2.4 Ensuring Consistency and Convergence

A critical aspect of MRM is to ensure consistency between the performance measures at different levels. This section discusses methods to ensure consistency of the capacity estimation, performance measure estimation, and demand estimation. Traditionally, MRM has been conducted in a one-way progression from course to fine-grained analysis. However, there is a need for a feedback loop in an iterative process to converge to a consistent solution by providing information from the upper (lower resolution) level to the lower (higher resolution level). This feedback loop for example can involve the provision of information based on the output of microscopic simulation tools for use in fine-tuning mesoscopic and macroscopic model parameters. It can also include using information from the mesoscopic model to inform the upper-level macroscopic model. Without consistency assurance between the different modeling resolutions, the assignment results and discrete choice modeling results from the upper level will produce unrealistic results when examined using microscopic simulation, resulting in gridlock in the simulation.

The consistency assurance should address the consistency in capacity/throughput specification between different levels. It is recognized that the capacity is an input to macroscopic models but is an output in some mesoscopic models and all microscopic models as it is assessed based on the microscopic traffic flow parameters by the models. Thus, these parameters will have to be fine-tuned to produce consistent capacities between the different levels.

There is a need to adjust the macroscopic and microscopic traffic flow parameters in the different levels of the analysis to ensure performance consistency between the different levels, given the demands and capacities. This includes at a minimum the travel time estimates by different models. To achieve this consistency, the analyst can calibrate the parameters of the volume-delay function like the Bureau of Public Work (BPR) function in the macroscopic model based on the output from the simulation models. The turn movement traffic flow parameters can be adjusted also to produce the expected delays as assessed by microscopic simulation models. It is recommended that this relationship between the volume to capacity ratio and travel time/delay is plotted for the critical segments and turn movement in the network to determine the need to fine-tune the model parameters to ensure consistency.

It should be mentioned that even with the capacity and traffic flow model calibration, some inconsistencies between the performance measures estimated by the models are expected. The volume-delay function may not produce realistic results for oversaturated conditions, particularly if it is calibrated at the subnetwork-wide level rather than the segment level. Mesoscopic simulation may not be able to assess all traffic operations impacts. For example, mesoscopic models may not be able to model the effect of spillover from the left-turn bay to the through movement lanes and the impact of lane changing maneuvers on traffic flow. However, the analyst should try to achieve consistency as much as possible. This will require an iterative process to modify parameters in the macroscopic and mesoscopic models to reflect various impacts observed in the microscopic model.

An important component of MRM is traffic assignment. Traffic assignment is categorized as static traffic assignment (STA) and dynamic traffic assignment (DTA). Traffic assignment involves an iterative process to reach user equilibrium to emulate drivers' selection of their routes. The convergence of user equilibrium assignment is necessary to ensure the integrity of the solution and critical when assessing alternative designs and operational strategies. A widely used measure for convergence is relative gap, which measures the difference between the current iteration solution and the ideal solution. The user of MRM needs to ensure convergence and understand the convergence process, criteria, and impact.

5.3 UTILIZING CROWDSOURCED DATA IN ORIGIN-DESTINATION MATRIX ESTIMATION (ODME) PROCESS

Origin-destination demand estimation is a vital part of MRM. The resulting traffic O-D demand matrices are used as inputs to static and dynamic traffic assignment models that are important components of the MRM. Often, in current practices, the traffic O-D demands used as inputs to the traffic assignment are extracted for a subnetwork from the larger networks modeled in existing regional travel demand models. However, modelers are often challenged with the inadequate quality of the O-D demand matrices obtained from demand forecasting models, which result in large errors in the link counts resulting from the assignment compared to real-world counts (Hadi et al. 2022). This implies the need for further refinement of the ODME procedures and the use of additional data sources as inputs to these procedures to allow these models to produce results that are acceptable for simulation modeling. In many cases, modelers have used ODME procedures that utilize a combinations of traffic counts and initial O-D demand matrices obtained from the demand models to obtain better estimations of the O-D demand matrices. Still, questions remain about the quality of the O-D matrices resulting from the ODME procedures. This chapter explores the possibility of including crowdsourced data sources into the ODME process and evaluates the quality of the resulting O-D matrices.

5.3.1 Utilized ODME Procedures

Multi-resolution simulation and the associated dynamic traffic assignment requires accurate time-dependent origin-destination matrices (e.g., 15 minute to one hour matrices). Demand forecasting models like the Florida Standard Urban Transportation Model Structure (FSUTMS) models produce O-D matrices for the whole peak period (e.g., two or three hours) rather than for short term periods as required by the multi-resolution models. In addition, assigning the O-D matrices generated using the demand forecasting models without corrections to these matrices generally results in link and turn movement volumes that can deviate significantly from real-world measurements. For this reason, origin-destination matrix estimation (ODME) procedures have been developed to produce time-variant O-D matrices that result in better segment and turn-movement volumes when assigned to the network compared to the use of the O-D matrices generated by the demand forecasting models.

Existing ODME procedures are provided with both commercially available and open-source demand forecasting and assignment tools. These procedures can update initial O-D demands, such as those generated by the demand forecasting models to improve their quality based on collected traffic count data and, sometimes, other performance measures such as travel time data. The procedures allow the O-D demand to produce link volumes that better correspond to real-world traffic counts when used in traffic assignment. The ODME procedures in these tools generally utilize optimization algorithms to estimate the O-D matrices by minimizing the errors between the model outputs and the inputs such as the seed O-D matrix, traffic count measurements, and so on. The user can provide weights in the optimization on the seed matrix and the other measurements such as the traffic counts, reflecting the level of trust that the user has in the input variable accuracies. This optimization results in improved O-D demand matrices compared to the O-D matrices generated by demand forecasting models. Input variables such as link and/or turning movement counts as well as initial O-D matrices are often used to seed the optimization process alongside other variables such as the attractions and production demands per zone. Some of the latest tools provide the advantage of using additional measures such as travel time, queue lengths, and densities as inputs to the ODME process.

. Modelers usually perform ODME procedures with or without a seed O-D demand matrix. Although the quality of the ODME output vastly depends on the availability of high-quality initial O-D demand matrices (Lin & Chang, 2006), modelers often choose to ignore the use of O-D matrices as seed matrix and rely on count data only. A common practice is to combine traffic volume measurements with initial O-D matrices obtained from demand forecasting models that are used as seed matrices. Also, partial O-D demand matrices obtained from automated roadside readers, such as Bluetooth readers and license plate readers, vehicle tracking using crowdsourced data such as global positioning system (GPS) data, and other data sources, are used as seed matrices to the O-D demand estimation (Hadi et al., 2022a, 2022b).

The ODME algorithms produce O-D demands that minimize deviations from the counts and seed matrices. In the ODME process, analysts can assign relative weights on different variables included in the optimization objective function to reflect the level of confidence in the data used to estimate the variables. In the mesoscopic simulation tool utilized in this study, weight ratio can be assigned, which reflects the relative weight of the seed matrix to traffic counts in the optimization process. For instance, analysts may assign a lower weight ratio if there is a higher confidence in the quality of the traffic counts compared to the quality of the seed O-D demand matrices.

This study investigated the performance of twelve different variations of the ODME processes. These variations use different combinations of initial O-D matrices from the regional demand forecasting model and crowdsourced data from a third-party vendor. The ODME procedures used in this study are provided with the PTV VISUM modeling tool (PTV Group, 2013). VISUM can be used to provide both macroscopic and mesoscopic levels of modeling as part of an MRM implementation. VISUM has two default ODME algorithms, the least-square and the TFlowfuzzy methods (PTV Group, 2013). The least-square method minimizes the squared distance between the assignment link volume value and the count value. In addition, it also allows the analysts to limit the deviation from the initial O-D matrix that is used as an input to the ODME process by minimizing the squared distance between the initial and modified trip demand values (Hadi et al., 2022a, 2022b). This method has other advantages, such as short run time, adaptability to large networks, and simplicity. Hadi et al. reported better results when using the least square algorithm for a case study compared to the results from using the TFlowfuzzy algorithm (Hadi et al., 2022a, 2022b). Thus, the least square method is used in this analysis.

5.3.2 Network Preparation

The case study network is located in downtown West Palm Beach, Florida, which was originally extracted as a subnetwork from the regional demand forecasting model. The regional model is referred to as the Southeast Florida Regional Planning Model (SERPM 7.0) (FSUTMSOnline, 2021). The extracted subnetwork consisting of the base geometry and initial O-D matrices for the year 2015 was exported to VISUM in a previous project conducted for Palm Beach County (Hadi et al., 2022a, 2022b). The already exported network to the VISUM model in the above-mentioned project was used in this study. The study area consists of 35 signalized and 38 unsignalized intersections. For completeness and future usage, the previously developed VISUM model includes additional segments and intersections outside the boundaries of downtown West Palm Beach, as indicated by the red lines on the map in Figure 5-1. Throughout the study, this case study network is referred to as the “West Palm Beach” network.

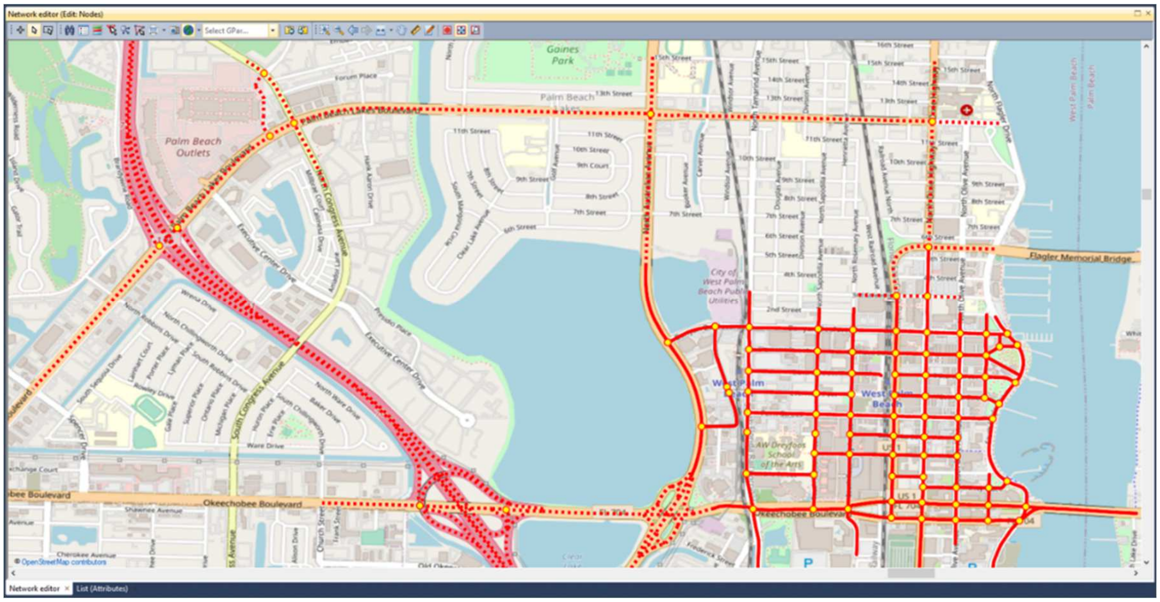


Figure 5-1 Screenshot of expanded West Palm Beach area in VISUM (Hadi et al. 2022).

5.3.3 Integration of Crowdsourced Data

In this study, StreetLight (SL) is used as the provider of the crowdsourced data. There are 93 traffic analysis zones (TAZs) in the West Palm Beach network that have been used in the case study. Figure 5-2 shows these zones as highlighted in the SL analysis dashboard display.

Figure 5-2 StreetLight analysis dashboard of the West Palm Beach network

After selecting the corresponding zones in the SL platform, the SL index value for each O-D pair in the network is obtained from the analysis report generated by the platform. As described earlier, the SL index is a normalized mobile parameter updated each month based on the ratio of the mobile sample available for a location to the total population (collected from the census block). Since the utilized mobile units represent only a fraction of the total numbers of vehicles, the absolute number of trips between the zones cannot be estimated without combining the SL index with other information. However, the SL Index can be used in combination with other data to provide an estimate of the number of trips between any two locations.

In this study, to compute the number of trips between an origin zone and a destination zone, the "SL index proportions" are computed. The SL index proportions is the ratio of the SL index for each O-D pair to the sum of the SL Index values between the origin and all destinations.

In addition to providing the SL Index values, StreetLight provides the users with an option to collect estimated demands from a specific origin zone to a destination zone. The vendor calculates these demands by expanding the mobile data using count data obtained from other sources. These demands referred to as the "SL Expanded" in this study are obtained using a proprietary machine-learning algorithm that uses the SL Index values and ground truth data as inputs (StreetLight Insight 2020 Whitepaper Version 1).

5.3.4 O-D Matrix Development Methods

This study explores twelve variations of the O-D matrix estimation procedure with and without the use of crowdsourced data. As stated earlier, the least square algorithm was utilized to perform the ODME procedure. The ODME procedure used in this study is an assignment-based procedure which utilized the static traffic assignment option in this study. A comparative analysis is performed between all of the investigated methods to identify the best way to develop an O-D matrix. This section describes each method and the use of different weight ratios on the inputs. The methods can be categorized into four different types – Category 1 through Category 4. Methods in Category 1 use an initial O-D matrix from the regional demand model (SERPM 7.0) with relative weights on the initial matrix of 0, 1 and 10 (as defined earlier, the relative weight is used such that the optimization process puts more or less emphasis on the initial O-D matrix relative to the real-world count measurements. The lower the weight the less is the emphasis on the initial matrix with 0 weight indicting no consideration of the demand matrix in the estimation). Methods in Category 2 are produced by using an initial O-D matrix that is generated by multiplying the sum of the production trips of each origin as estimated by SERPM 7.0 by the proportion to each destination as estimated by the SL Index proportions, since the SL index values do not provide the actual demands. Thus, the demand forecasting model is used to estimate the overall trip generation, while the SL Index is used to estimate the distribution. Methods in Category 3 are similar to the methods in Category 2, but instead of using the trip generation based on SERPM 7.0, the trip generation is based on the results from the Category 1 method with a relative weight of ten. The rationale is that the refined O-D matrix based on both count data and an initial O-D matrix from SERPM 7.0 can provide better trip generation than using trip generation based on the original O-D matrix obtained from the SERPM 7.0 model. Similar to the methods in Category 2, the SL Index proportions are used to distribute the trips to destination in methods from Category 3. The methods in Category 4 use the O-D matrix expanded by the vendor (StreetLight), which is referred to as the SL Expanded. The twelve methods within these four categories are described in the following text.

- Method Category 1: The seed matrix used in this category is the initial O-D matrix obtained from SERPM 7.0.
    - Method 1: This is a Category 1 method with no ODME (uses the O-D matrix obtained from SERPM 7.0 in the assignment process).
    - Method 1(a): In this method, the ODME procedure is implemented with a relative weight on the seed matrix of zero, indicating that the ODME procedure will estimate the O-D matrix based on the link count only. In other words, this method does not consider the impact of the seed matrix.
    - Method 1(b): Method 1(b) implements the ODME procedure with a relative weight of ten on the O-D matrix obtained from SERPM 7.0 (the seed matrix) to put more emphasis on the seed matrix than the count deviation.
    - Method 1(c): Method 1 (c) is similar to Method 1(b), but with a relative weight of one to put equal weight on the count and seed matrix in the ODME process.
- Method Category 2: As explained earlier, the methods in this category use the trip generation from demand forecasting model (SERPM 7.0) and calculated trip distributions based on the SL Index.
    - Method 2: This is a Category 2 method with no ODME (uses an O-D matrix with trip generation from the O-D matrix obtained from SERPM 7.0 and trip distribution based on the SL Index proportion in the assignment process).
    - Method 2(a): This is a Category 2 method with a relative weight of ten on the initial O-D matrix in the ODME process.
    - Method 2(b): This is a Category 2 method with a relative weight of one on the initial O-D matrix in the ODME process.
- Method Category 3: This Category is similar to the Method Category 2 but with the use of trip generation based on the O-D matrix resulting from Method 1(b) rather than based on the original O-D matrix from SERPM 7.0. As with the methods in Category 2, the SL index proportion is used for trip distribution.
    - Method 3: This is a Category 3 method with no ODME (uses an O-D matrix with trip generation from the O-D matrix obtained from Method 1b and trip distribution based on the SL Index proportion in the assignment process).
    - Method 3(a): This is a Category 3 method with a relative weight of ten on the initial O-D matrix in the ODME process.
    - Method 3(b): This is a Category 3 method with a relative weight of one on the initial O-D matrix in the ODME process.
- Method Category 4: The utilized matrix in Method 4 is the default SL expanded O-D matrix provided by the vendor (i.e., matrices estimated by SL without any ODME procedure implemented on the resulting O-D matrix).
    - Method 4: This is a Category 4 method with no ODME (uses the SL Expanded O-D matrix in the assignment process).
    - Method 4 (a): This is a Category 4 method with a relative weight of ten on the initial SL Expanded O-D matrix in the ODME process.

5.3.5 Performance Measures of O-D Matrix Estimation Methods

The performance of the O-D matrix estimation was assessed based on the deviation of the resulting counts from the assignment compared to the real-world counts and based on the deviation from the available O-D matrices (the matrix obtained from the demand forecasting model and the matrix obtained based on crowdsource data from Streetlight).

Deviations from Link and Turn Volume Counts

First the deviation of the resulting volumes from assigning the O-D matrices from the real-world link and turn volume counts are compared. Instead of a single performance indicator, three performance indicators were used to evaluate the performance of different methods in this study. The following three performance metrics (Equations 5-1 to 5-3) were used to evaluate the accuracy of the O-D matrix development methods:

1. Root Mean Squared Error (RMSE): RMSE measures the error of the prediction model. The distance between the predicted values and the benchmark values is squared and averaged over the sample dataset. Since the errors are squared before it is averaged, RMSE puts a high weight to large deviations compared to the absolute mean error measures. As a result, RMSE is a good indicator when large errors are undesirable.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (\acute{x}_i - x_i)^2}{n}} \qquad (5\text{-}1)$$

where
$\acute{x}_i$= benchmark traffic volume for link/turn movement i;
x_i= estimated traffic volume for link/turn movement i; and
n = number of estimate-to-benchmark comparisons.

2. Mean Absolute Error (MAE): MAE is the average of the absolute distance between each estimated data value and the benchmark value. The MAE is a linear score which puts equal weight on the individual differences in the average. A small MAE indicates that the data values are close to the benchmark data.

$$MAE = \frac{}{n} \times \sum_{i}^{n} \quad |x_i - \acute{x}_i| \qquad (5\text{-}2)$$

where
$\acute{x}_i$, x_i and n are as previously defined in Equation (5-1).

3. Mean Absolute Percentage Error (MAPE): MAPE is the average of the absolute percentage errors of the predicted value. MAPE is scale-independent and widely used due to easy interpretation of the deviations from the benchmark data.

$$MAPE\ (\%) = \frac{00}{n} \sum_{i}^{n} \quad \frac{|x_i - \acute{x}_i|}{\acute{x}_i} \qquad (5\text{-}3)$$

where
$\acute{x}_i$, x_i and n are as previously defined in Equation (5-1).

Table 5-1 shows an overall comparison of the performance measures computed based on Equations 5-1 to 5-3 to indicate the deviation or the fit of the resulting link and turn movement volumes compared to real-world counts for different ODME estimation methods. The deviation from the Streetlight and SERPM matrices are discussed later in this section. As expected, Method 1(a) produced the least deviation or best fit in terms of the counts since it only considers the count in the optimization (no seed matrix from SERPM or Streetlight). Thus, it is expected to produce the best result from count point of view, but it is expected to result in a matrix that is far away from SERPM and Streetlight matrices. Also, as expected, Method 1 produced the worst fit in terms of the counts since it does not consider the count in the optimization. Although Method 1(a) produced good results in terms of counts, it is not a good method to use because of the large deviation from the initial O-D matrices. Among all other methods, Method 1(b) and Method 3(b) produced the best fit to real-world count that is in fact comparable to that of Method 1(a). Thus, these methods are candidates for use subject to examining the deviations from the O-D matrices, as will be discussed. Method 1(b) uses the regional demand model O-D matrix as a seed matrix with a relative weight of ten. Method 3(b) uses a first ODME process with a seed O-D matrix from the regional model then redistribute the trips based on the SL Index proportions. The resulting O-D matrix is used with a relative weight of one in a second ODME process to produce the final O-D matrix.

Table 5-1 Comparison of the deviations of link and turn volumes resulting from the assignment, from real-world counts

Method				RMSE		MAE (vph)		MAPE (%)	
ID	**Seed Matrix**	**Relative Weight**	**ODME**	**Link**	**Turn**	**Link**	**Turn**	**Link**	**Turn**
1	None	N/A	No	769	394	513	249	138	252
1(a)	None	0	Yes	68	76	46	39	20	50
1(b)	SERPM	1	Yes	87	85	52	48	20	60
1(c)	SERPM	10	Yes	903	741	593	379	170	356
2	SERPM x SL Index	N/A	No	156	108	92	59	33	61
2(a)	SERPM x SL Index	10	Yes	1172	779	601	341	116	211
2(b)	SERPM x SL Index	1	Yes	1172	779	601	341	116	211
3	Production of 1(c) x SL Index	N/A	No	99	96	67	53	30	60
3(a)	Production of 1(c) x SL Index	10	Yes	708	616	331	271	90	170
3(b)	Production of 1(c) x SL Index	1	Yes	71	84	47	43	20	50
4	SL Expanded	N/A	No	315	303	166	159	42	94
4(a)	SL Expanded	10	Yes	142	99	77	55	27	60

Note 1: As explained earlier, the relative weight is used such that the optimization process puts more or less emphasis on the initial O-D matrix relative to the real-world count measurements. The lower the weight the less is the emphasis on the initial matrix with 0 weight indicting no consideration of the demand matrix in the estimation.

Note 2: The deviation of the link volumes from the real-world link counts referred to as "Link," and the deviation of the turn movement volumes from the real-world counts referred to as "Turn" in the table.

Deviations from the Available O-D Matrices

After carefully considering the results of the investigation of the deviations from (fit to) the ground truth traffic counts of the ODME methods presented in the above discussion, this study then compares the deviations for the available O-D matrices resulting from some of the investigated methods. As stated in the previous section, Method 1(b) and Method 3(b) exhibited low deviations from the link and turn counts that are close to the deviations obtained with Method 1(a) that uses no seed matrix in the ODME. These methods are candidates to be recommended for use in the ODME process. However, further analysis is needed to determine the degree of deviation from the available O-D matrices of the investigated methods.

To illustrate the trend in the deviation of demands between the O-D pairs of individual methods, each method is compared to the O-D matrix from the demand model and the O-D matrix based on the SL Expanded matrix. Table 5-2 shows the distribution of mean absolute errors (MAE) of the O-D pair demands among the three matrices for the two candidate methods (1b and 3b) compared to the base method (Method 1a). The errors are categorized into seven intervals, as follows: errors that are equal to 0, errors that are between 0 and 50 vehicles (0<MAE<50), errors that are between 50 and 100 vehicles (50≤MAE<100), errors that are between 100 and 300 vehicles (100≤MAE<300), errors that are between 300 and 500 vehicles (300≤MAE<500), errors that are between 500 and 1,000 vehicles (500≤MAE<1000), and errors that are greater than 1,000 (≥1000).

Table 5-2 shows the MAE of the resulting O-D matrix compared to the SERPM 7.0 matrix and SL Expanded matrix for the ODME methods. Method 1(a), where no initial seed matrix was used, produced high overall deviation from both the SERPM 7.0 and SL Expanded matrices of about 56% and 55%, respectively. Method 1(b), which uses the SERPM 7.0 O-D matrix as an initial O-D matrix with a relative weight of ten in the ODME, resulted in high deviation from both SERPM 7.0 (about 55%) and SL Expanded (about 54%). However, in terms of large errors (MAE >300), Method 1(b) has only six large error counts, compared to 17 large errors in Method 1(a), when compared to the default SERPM 7.0 O-D matrix. Method 3(b) generated significantly lower overall deviations from SL estimates (19%) with comparable deviations from the SERPM model O-D matrix (62%).

Table 5-2 The fit of the O-D matrix produced from different methods to SERPM 7.0 and SL Expanded O-D matrices

(a) Method 1(a) – Relative Weight = 0 (no Seed Matrix)

Method 1 (a)	Relative to SERPM 7.0		Relative to StreetLight Expanded	
MAE by Error Range (Vehicle per PM Peak Period)	Frequency Count	Frequency Percentage	Frequency Count	Frequency Percentage
≥1000	1	0.01%	0	0.00%
500≤MAE<1000	6	0.07%	5	0.06%
300≤MAE<500	10	0.12%	6	0.07%
100≤MAE<300	38	0.44%	33	0.39%
50≤MAE<100	79	0.92%	51	0.60%
0<MAE<50	4671	54.59%	4656	54.42%
MAE = 0	3751	43.84%	3805	44.47%
Sum of O-D pairs with errors	4805	**56.16%**	4751	**55.53%**
Total number of O-D pairs	8556	100%	8556	100%

(b) Method 1(b) – Seed Matrix: Method 1, Relative Weight = 10

Method 1 (b)	Relative to SERPM 7.0		Relative to StreetLight Expanded	
MAE by Error Range (Vehicle per PM Peak Period)	Frequency Count	Frequency Percentage	Frequency Count	Frequency Percentage
≥1000	0	0.00%	0	0.00%
500≤MAE<1000	2	0.02%	3	0.04%
300≤MAE<500	4	0.05%	5	0.06%
100≤MAE<300	42	0.49%	37	0.43%
50≤MAE<100	91	1.06%	63	0.74%
0<MAE<50	4627	54.08%	4547	53.14%
MAE = 0	3790	44.30%	3901	45.59%
Sum of O-D pairs with errors	4766	**55.70%**	4655	**54.41%**
Total number of O-D pairs	8556	100%	8556	100%

(c) Method 3(b) – Seed Matrix: Method 3, Relative Weight = 1

Method 3 (b)	Relative to SERPM 7.0		Relative to StreetLight Expanded	
MAE by Error Range (Vehicle per PM Peak Period)	Frequency Count	Frequency Percentage	Frequency Count	Frequency Percentage
≥1000	1	0.01%	0	0.00%
500≤MAE<1000	5	0.06%	3	0.04%
300≤MAE<500	7	0.08%	2	0.02%
100≤MAE<300	49	0.57%	33	0.39%
50≤MAE<100	93	1.09%	59	0.69%
0<MAE<50	5155	60.25%	1514	17.70%
MAE = 0	3246	37.94%	6945	81.17%
Sum of O-D pairs with errors	5310	**62.06%**	1611	**18.83%**
Total Cells	8556	100%	8556	100%

5.3.6 Summary

This study compared 12 variations of the ODME process utilizing different combinations of real-world count data, initial O-D matrices obtained based on crowdsource data from Streetlight, and/or initial O-D matrices from the regional demand forecasting model (SERPM) as inputs to the optimization process. The input variables were used in the optimization utilizing different methods and the relative weights assigned to these variables were also varied in the optimization.

As expected, the assignment of the O-D matrix extracted from SERPM without refinement using the ODME process results in large deviations of the assigned volumes from real-world counts. On the other hand, obtaining the O-D matrix using solely the real world counts as inputs to the optimization process (i.e., using no initial O-D matrix as input to the optimization) result in a large deviation from the O-D matrix produced by SERPM and the O-D matrix obtained based on Streetlight data.

Based on the analysis presented in this study, Method 3(b) produced the best results considering that it produced low deviations from the real-world counts and the O-D matrix obtained based on Streetlight data. It also produced comparable deviations from the regional demand model O-D matrix to the deviations obtained with the other methods. The steps of Method 3(b) are listed below. Please, note that the relative weights in Steps 1 and 3 can be changed by the user depending in their confidence in the accuracy of different input variables.

- Step 1: an ODME procedure is run using the count data and O-D matrix obtained from the demand forecasting model with a relative weight of ten on the O-D matrix. Crowdsource data is not used here since crowdsource data is not expected to produce good estimates of the demands due to the small sample sizes.

- Step 2: the trip generated according to the O-D matrix derived in Step 1 are redistributed based on the SL Index proportions obtained from the acquired crowdsource data. The estimation of the proportions of the trips going to each destination based on the SL index proportions are expected to be more accurate than the proportions based on the demand forecasting models since they are based on real-world measurements.

- Step 3: A second ODME process is conducted with an initial O-D matrix obtained from Step 2 with a relative weight of 1 on the O-D matrix to obtain closer results of the resulting assigned volumes to real-world traffic counts.

5.4 USING CROWDSOURCED DATA FOR SEGMENT-LEVEL VOLUME COUNT ESTIMATION

In addition to providing data that can be used for O-D matrix estimation, crowdsourced data have been proposed to provide estimates of daily and hourly traffic volume counts. Such estimates can be used to provide support to analysis, simulation, and MRM, as volume count data is expensive to collect and in many cases, counts are available only for short periods of time and may not cover all links in the network. This study investigated utilizing crowdsourced data in combination with the real-world data collected from permanent detectors at specific locations to estimate the link volumes and discusses the assessment, the accuracy, and the transferability of using the data for link volume estimation.

5.4.1 Existing Volume Count Data

Data from the same West Palm Beach network presented in Chapter 4 are used in the development and assessment of the method to estimate the volume counts based on SL data in this chapter. There are two permanent count stations (PCS) maintained by the Florida Department of Transportation (FDOT) in the case study network. The first is located near the Flagler Memorial Bridge (Site 0087), while the second is on I-95 (Site 0174), as indicated by the red circles in Figure 5-3. The whole year traffic volumes from these two permanent count stations are used in this study. The year-long data from 2020 is collected from Florida Traffic Online, which is an online tool established and maintained by the FDOT.

Figure 5-3 StreetLight analysis dashboard of the West Palm Beach network

5.4.2 Seasonal Variations in the Data

The first question to be answered is whether crowdsourced data can provide enough information to determine the seasonal variation in the data. This is important because an analyst may need to conduct multiscenario analysis or need to estimate the traffic volumes in the peak season of the year based on data collected in other seasons. This section compares seasonal variation in average daily traffic (ADT) from the PCS (used in this case as benchmark data) with the variations based on the SL Expanded volume, in vehicles per day (vpd). The monthly average daily traffic (MADT) of June, July and August are aggregated to represent the summer season ADT and the MADT for December, January and February, which are aggregated to represent the winter season ADT. The traffic demand is expected to be higher during the winter season in West Palm Beach, Florida, compared to the summer.

Table 5-3 compares the seasonal variation in the ADT based on the PCS and SL Expanded (SL

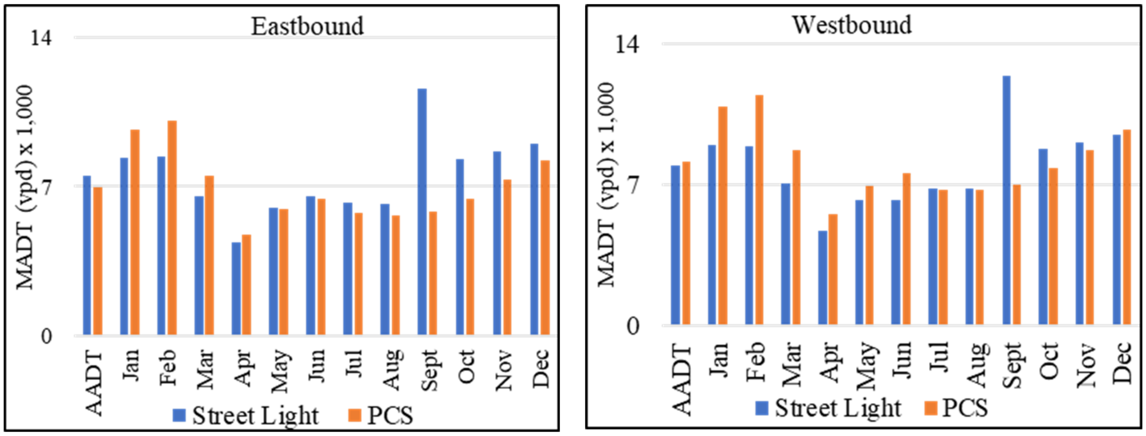
Exp) data in the two locations where PCSs are present, as discussed earlier. The two locations are the Flagler Memorial Bridge for eastbound and westbound traffic, and the I-95 Congress location for northbound and southbound traffic. As shown in Table 5-3, the seasonal factors (SF) were calculated for PCS and SL Expanded data sources. For instance, the summer SF is calculated by dividing the summer ADT based on the three months (i.e., June, July, and August) over the ADT based on all six months. It is evident that there is a significant difference of ADT in some cases, such as eastbound (EB) (28%) and westbound (WB) (27%) during the summer season.

Table 5-3 Seasonal ADT comparison SL Expanded vs PCS counts

	Flagler Memorial Bridge				I-95 Congress			
	Eastbound		Westbound		Northbound		Southbound	
	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer
PCS (vpd)	28,004	17,823	32,073	21,072	322,701	258,266	326,074	259,769
SL Exp (vpd)	25,969	18,922	27,316	19,873	223,363	179,689	241,207	197,272
PCS SF	0.61	0.39	0.60	0.40	0.56	0.44	0.56	0.44
SL Exp SF	0.50	0.50	0.50	0.50	0.49	0.51	0.48	0.52
Percentage Difference	18%	28%	17%	27%	12%	15%	13%	16%

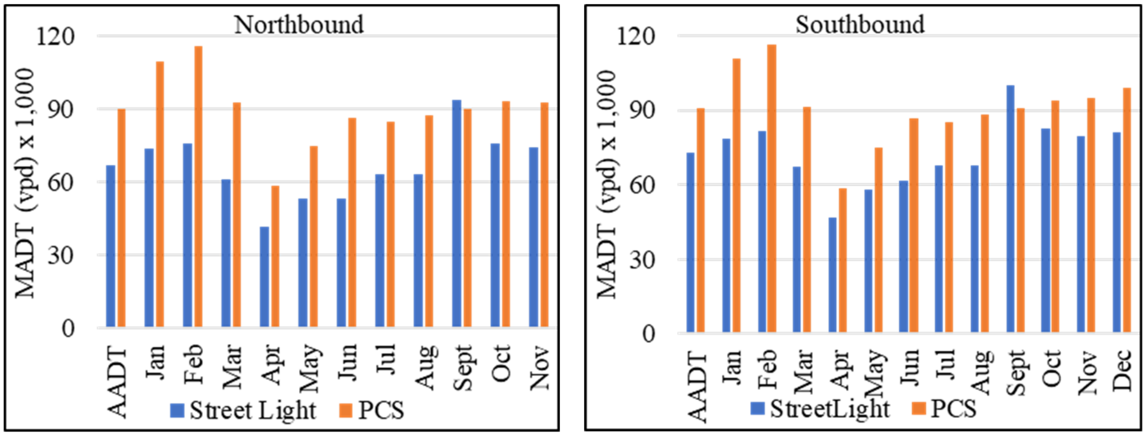
5.4.3 Comparison of Monthly Volumes between PCS and SL Expanded Data

Figure 5-4 shows a comparison of the MADT for each month of the year based on the data from PCS with those based on SL Expanded. Interestingly, for the eastbound (EB) and westbound (WB) directions at the Flagler Memorial Bridge location, the MADT estimates based on SL data are similar to the PCS data, except for the months of January, February, and September, as displayed in Figure 5-4(a) and Figure 5-4(b). The annual average daily traffic (AADT) for the eastbound direction is 6,961 vpd and 7,507 vpd based on PCS and SL data, respectively. The AADT for the westbound direction is 7,958 vpd and 8,157 vpd based on PCS and SL data, respectively. However, for the northbound (NB) and southbound (SB) directions of the I-95 location, the SL data underestimates the MADT compared to the PCS data in most cases, as seen in Figure 5-4(c) and (d). In terms of AADT at the I-95 location, high discrepancies are observed for both directions of I-95. The annual average daily traffic (AADT) for the northbound direction is 90,276 vpd and 66,944 vpd based on PCS and SL data, respectively. The AADT for the southbound direction is 90,836 vpd and 72,720 vpd based on PCS and SL data, respectively. The SL Expanded underestimation of the volume is possibly due to the expansion of the partial data by SL using data collected from other locations that have different characteristics or are less congested than freeway facilities in South Florida.



(a) – PCS on Flagler Memorial Bridge

(b) – PCS on Flagler Memorial Bridge



(c) – PCS on I-95

(d) – PCS on I-95

Figure 5-4 Comparison of MADT based on SL Expanded vs. PCS counts

5.4.4 Estimating Daily Volume at PCS locations Using Regression Analysis

The comparison in the previous section indicates that there are large discrepancies between the AADT and MADT estimated based on SL Expanded data and PCS data. This section presents and investigates an enhanced methodology to estimate the traffic volumes based on the SL Index values using a regression model to expand the data rather than using the SL Expanded data.

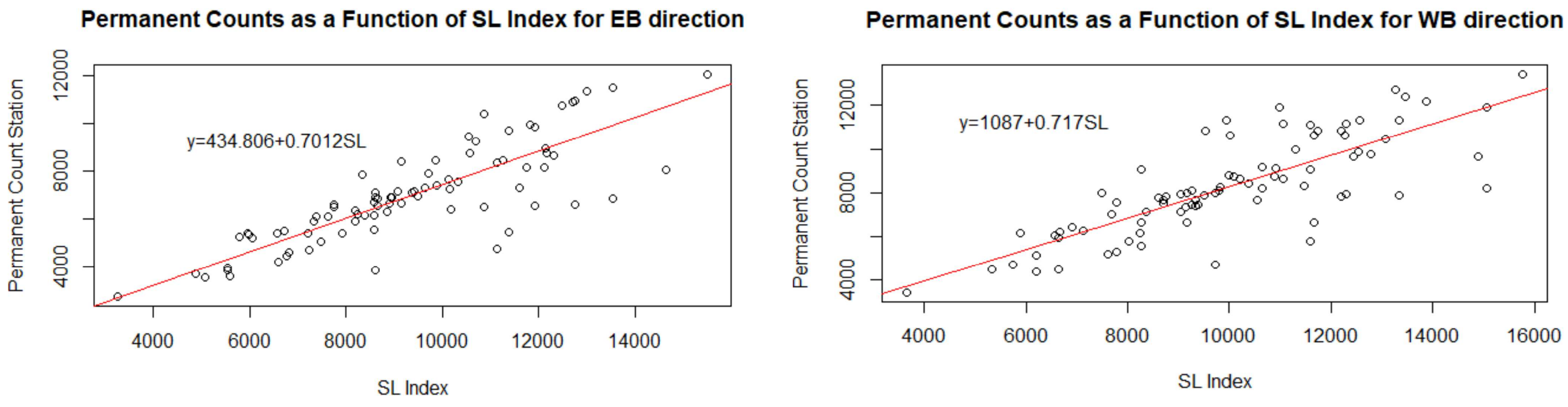
As discussed in Chapter 4, the SL index is a metrics used by SL to estimate features like segment-level volume, O-D trips, and turning movement volumes. The SL index is expanded by Streetlight to full counts based on data from ground truth locations that may not be in the same region or network of the study. Thus, it is expected that expanding the SL index values to full counts based on ground truth counts collected from the same network under investigation can produce better results. To develop and assess a method for SL Index expansion based on local network data, the relationship between the PCS values and the SL Index is fitted in a regression model, with the volumes based on the PCS values as the response or dependent variable (indicated as PCS in the regression equation in the following sections) and SL Index as the explanatory or independent variable (indicated as SL in the regression equations in the following sections). Data aggregated daily from eleven months chosen randomly out of the twelve months in the year 2020 are used as training data, and data from the remaining month is used as testing data in the regression model. For each month, data collected from the PCS and SL Index data for the same locations discussed in the previous section are averaged for each of the seven days in the week over the whole month, resulting in seven data points per month. For instance, all of the Mondays in one certain month are averaged. Similarly, the rest of the days in the month are averaged.

Regression models are fitted for the two different location sites in five variations, including a model for each of the four directions and a model with all four directions combined. The statistical inferences are summarized in Table 5-4. The R^2 value is a goodness-of-fit measure that indicates how much of the deviations in the dependent variable are explained by the independent variable in the fitted model. The higher the R^2, the better and more accurate the model is in predicting the real-world values using SL Index as an input. The fitted regression models, for every direction, have an R^2 greater than 60%, indicating that the models can predict more than 60% of the variation in the PCS values. The model developed with all directions has an R^2 of 97.6%, which is the best fitted model among all of the models. The p-value determines if the explanatory variable is significant in the model. A p-value less than a certain significance level, usually 5%, indicates that the explanatory variable is significant. In this case, all p-values are close to zero, indicating that, for all directions, the SL Index aggregated daily for every month is a significant predictor of PCS values. The R^2 and p-value results in Table 4-2 indicate that there is a significant relationship between the PCS count and SL Index.

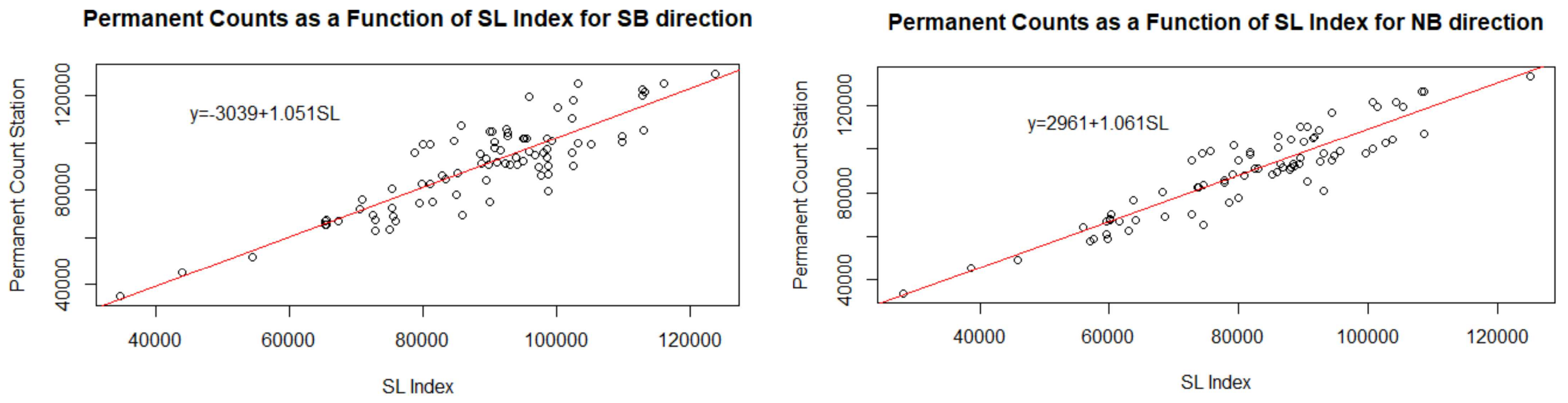
Table 5-4 Regression statistical inferences for PCS counts as a function of SL Index using daily data

Direction	Regression Equation	R^2	p-value
EB	PCS = 434.8060 + 0.7012SL	69.0%	0.000
WB	PCS = 1087.0000 + 0.717SL	62.0%	0.000
SB	PCS = -3039.0000 + 1.051SL	77.8%	0.000
NB	PCS = 2961.0000 + 1.061SL	83.8%	0.000
All Directions	PCS = -2531.0000 + 1.082SL	97.6%	0.000

The regression plots for the two different location sites in five variations, including a model for each of the four directions and a model with all four directions combined are shown in Figure 5-5 and Figure 5-6, respectively.



(a) For EB Direction **(b) For WB Direction**



(c) For SB Direction **(d) For NB Direction**

Figure 5-5 PCS counts vs. SL Index fitted regression model using daily volumes

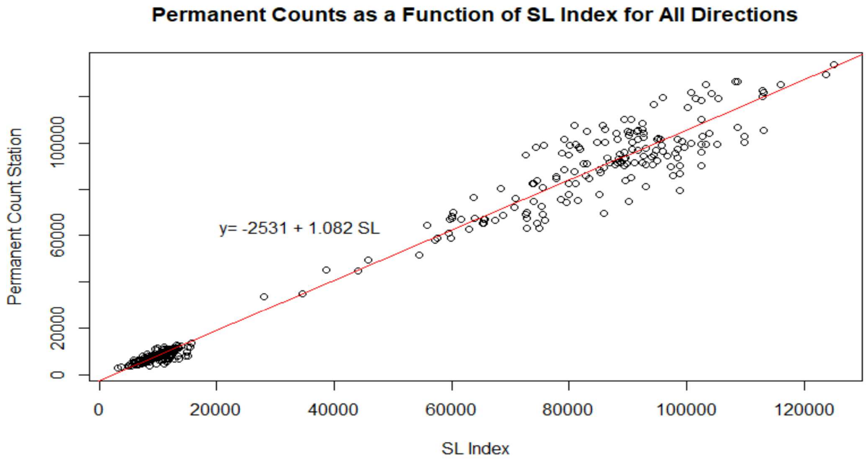


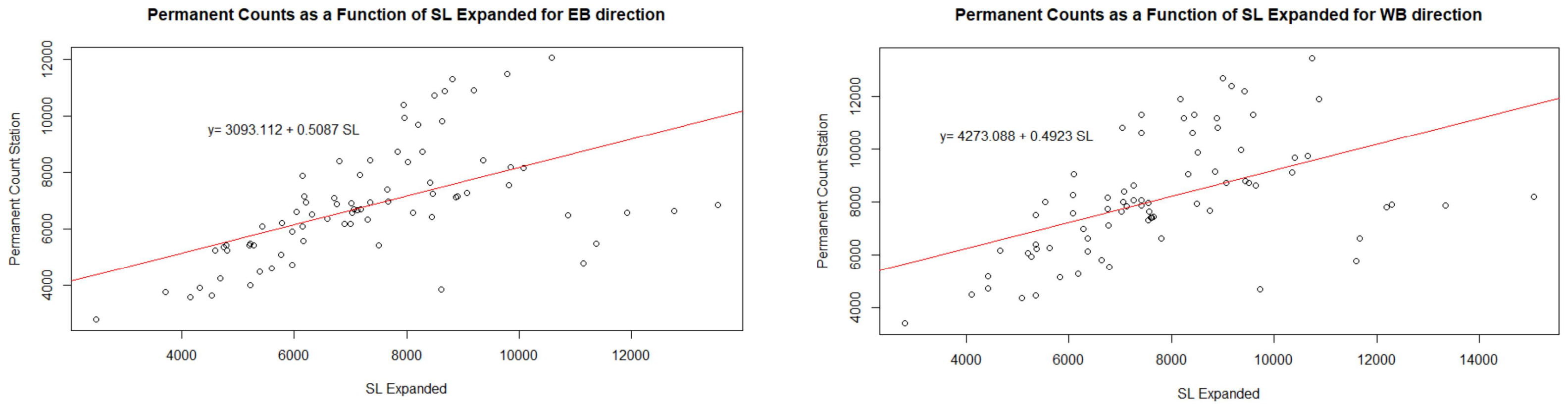
Figure 5-6 PCS counts vs. SL Index fitted regression model for all directions using daily volumes

Another approach to expanding the SL data based on the ground truth counts is to develop another regression model to correct the SL Expanded based on PCS data instead of using the SL Index as described above, again at the daily aggregation level, with the volumes based on the PCS values as the response or dependent variable (referred to as PCS in the regression equations) and SL Expanded as the explanatory or independent variable (referred to as SL in the regression equations). The statistical inferences of the fitted models are summarized in Table 5-5. The R2 values are relatively lower for all five models compared to the models developed earlier using the SL Index. The values are particularly low for the models developed based on the eastbound and westbound data, which are 24% and 29%, respectively. The lower R^2 values indicate that the models developed per direction for SL Expanded are not as accurate to predict the variations in the counts as the models developed based on the SL Index. However, the All Directions model still produced a very good fit with an R2 of 94.1%. The reason that the All Directions model produces better results than the individual direction model is expected to be due the coverage of a wider range of volumes from low to high volumes in the data used for the All Directions model. Overall, the regression models between the PCS counts and the SL Expanded volumes were less significant that those between the PCS counts and the SL Index.

Table 5-5 Regression statistical inferences for PCS counts as a function of SL Expanded using daily data

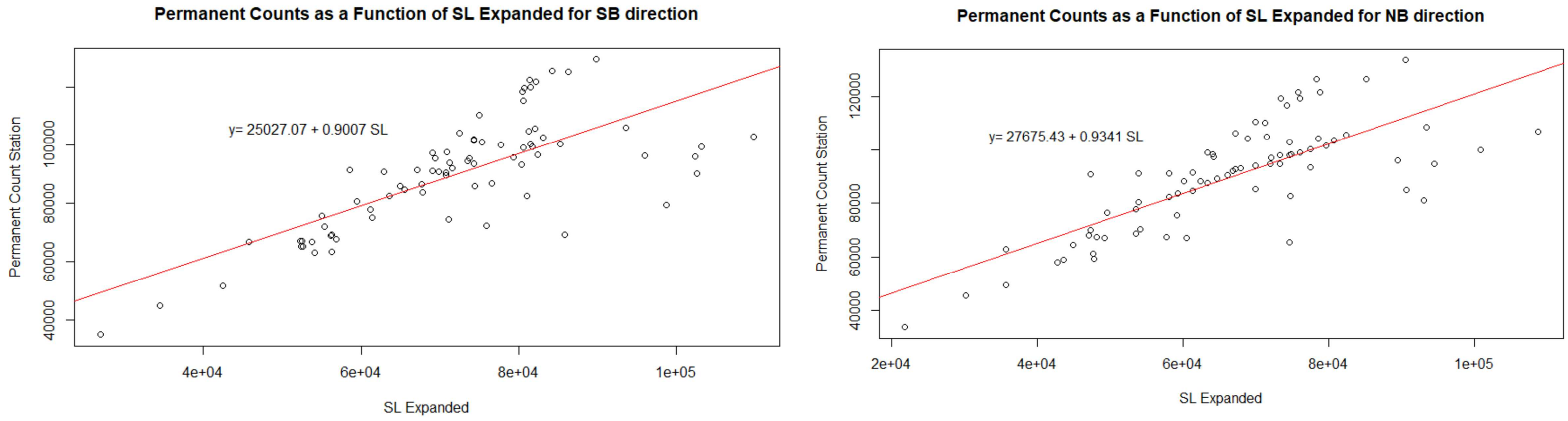
Direction	Regression Equation	R^2	p-value
EB	PCS = 3093.1120 + 0.5087SL	29.0%	0.000
WB	PCS = 4273.0880 + 0.4923SL	23.7%	0.000
SB	PCS = 25,027.0000 + 0.9007SL	53.9%	0.000
NB	PCS = 27,675.4300 + 0.9341SL	58.4%	0.000
All Directions	PCS = -547.0 + 1.281SL	94.1%	0.000

The regression plots along with the regression models are shown in Figure 5-7 for EB, WB, SB, and NB and in Figure 5-8 for all directions, respectively. Based on the statistical inferences from the above results, regression models developed based on the SL Index for daily volumes was selected for further analysis.



(a) For EB Direction

(b) For WB Direction



(c) For SB Direction

(d) For NB Direction

Figure 5-7 PCS counts vs. SL Expanded fitted regression model using daily volumes

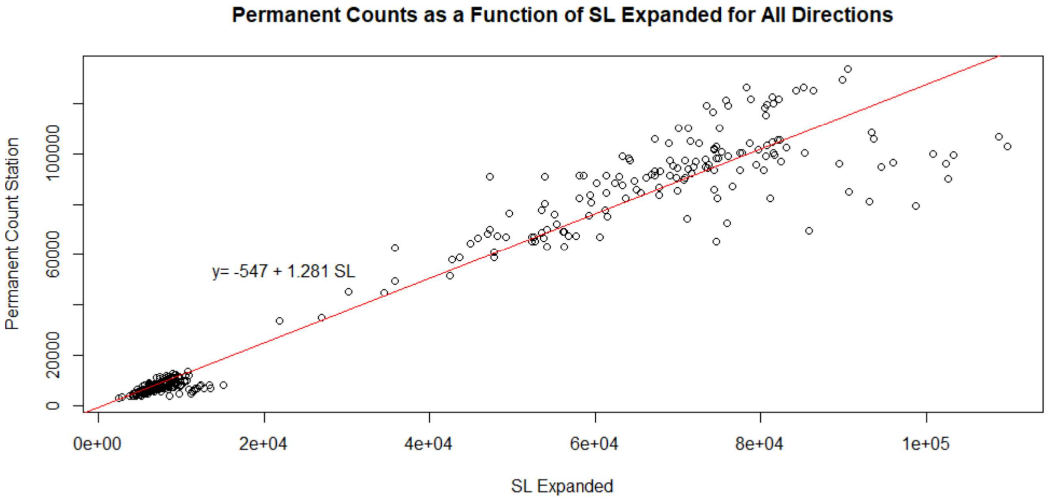


Figure 5-8 PCS counts vs. SL Expanded fitted regression model for all directions using daily volumes

The performance of the regression models developed based on SL Index to estimate the daily volumes are compared to the ground truth data collected from the PCS. Table 5-6 shows the MAPE computed for the training data and testing data for the two methods (expansion of SL Index based on local volume data, and the original SL Expanded volume data). As shown in Table 5-6, the use of the direction specific regression models based on the SL Index produced a MAPE of 5.35% to 8.14% for I-95 and 7.40% to 12.88% for the Flagler Bridge. Depending on the specific applications, these errors may or may not be acceptable. The above results indicate that the development of regression models between PCS data and SL data has the potential of providing acceptable results for daily volume estimation, particularly for higher volume segments. However, it should be remembered that the testing here is done using PCS Count and SL Index data from the same location from which the data is collect from for the regression. For the models to be useful, they need to be tested to estimate the volumes for locations other than the locations of the PCS station used in the regression. Such testing should be done in a future study.

Table 5-6 MAPE of SL Index regression models for daily volume estimation

Used Model	**Measure**	**Flagler Bridge EB**	**Flagler Bridge WB**	**I-95 NB**	**I-95 SB**
SL Estimates (SL Expanded)	MAPE Training Data	22.28%	19.96%	17.62%	20.20%
	MAPE Testing Data	8.00%	17.00%	36.00%	29.00%
Direction-Specific Linear Regression based on SL Index	MAPE: Training Data	12.63%	12.88%	7.53%	8.14%
	MAPE: Testing Data	7.40%	8.50%	6.10%	5.35%
All Direction Linear Regression based on SL Index	MAPE: Training Data	18.19%	16.05%	5.81%	9.01%
	MAPE: Testing Data	9.43%	7.58%	5.51%	8.87%

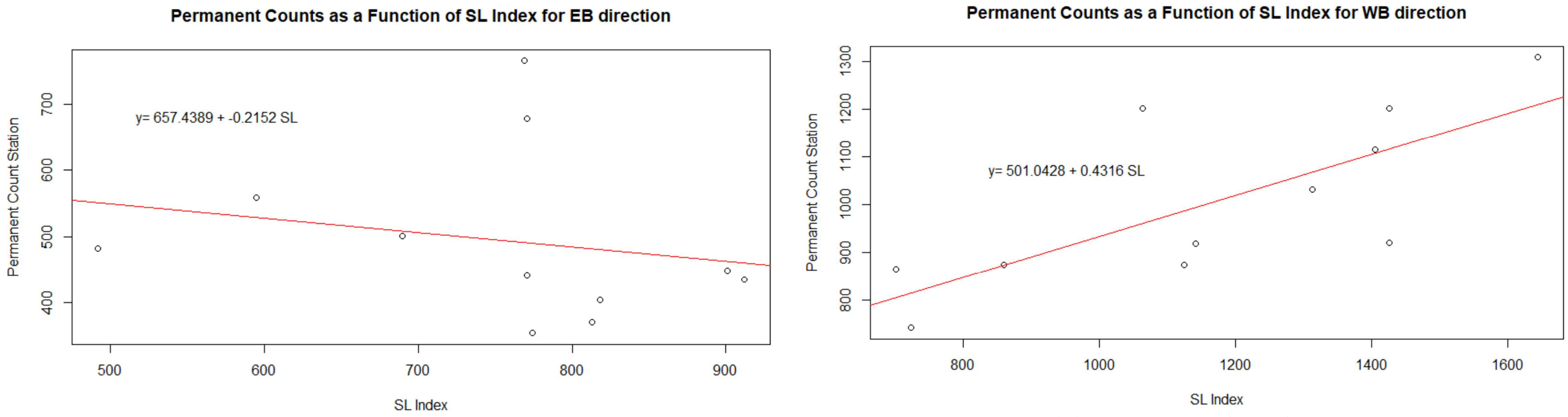
5.4.5 Estimating Hourly Volume at the PCS locations Using Regression Analysis based on SL Index

Considering the improvement in the AADT estimates based on the developed regression models in the previous section, additional work was done to investigate the estimation of the hourly traffic volumes using the same method. Regression models were developed between the hourly SL Index and PCS hourly volumes. The SL and PCS are divided into training datasets, consisting of data for 11 months, and testing dataset, consisting of data in the remaining (one) month. The PCS values are used as the response or dependent variable, and the SL Index as the explanatory or independent variable. The hourly volumes (vph) for all of the days of the week are manually averaged over the whole month. For instance, volumes for all of the Mondays at 4:00 PM are averaged over a certain month.

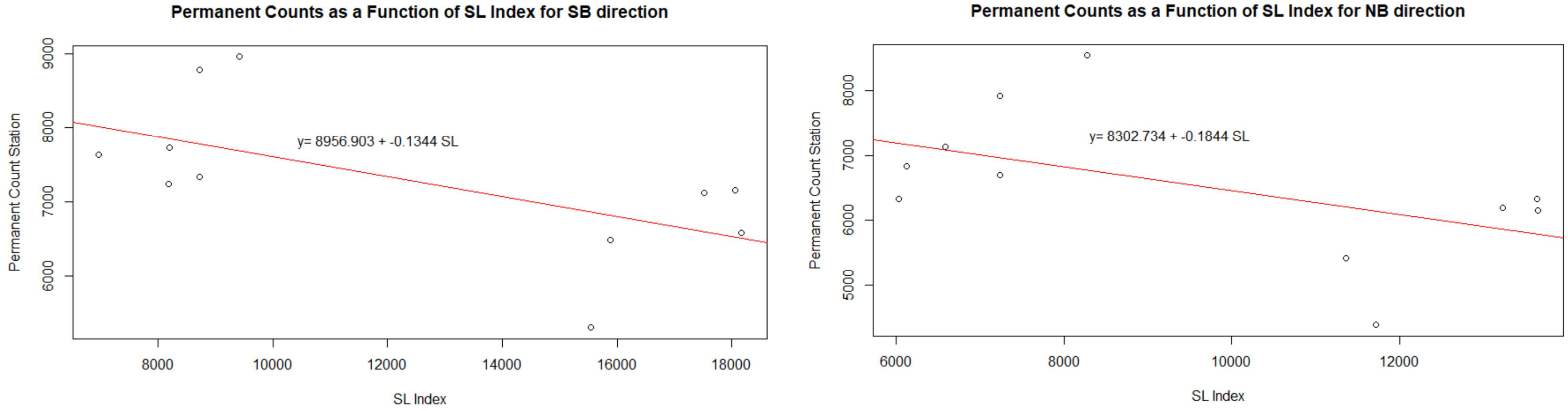
This study investigated three different variations of the regression models using the hourly volume data. These variations are explained next. In the first variation (Scenario 1), the data is averaged over all Tuesdays (typical weekday) per month from 4:00 PM to 5:00 PM, resulting in a total of 11 data points for the training dataset. Tuesday is selected as a typical weekday, and the timing from 4:00 PM to 5:00 PM is selected as a typical peak hour. The fitted regression models did not exhibit good performance as shown in Table 5-7, which summarizes the statistical inferences. The regression plots for Scenario 1 are included in Figure 5-9 and Figure 5-10 for further inferences.

Table 5-7 Regression statistical inferences for PCS counts as a function of SL Index for Tuesday peak hour

Direction	Regression Equation	R^2	p-value
EB	PCS = 657.4389 – 0.2152SL	4.4%	0.540
WB	PCS = 501.0428 + 0.4316SL	55.6%	0.010
SB	PCS = 8956.9030 – 0.1344SL	37.0%	0.050
NB	PCS = 8302.7340 – 0.1844SL	27.0%	0.100
All Directions	PCS = 1203.0 + 0.433SL	62.8%	0.000



(a) For EB Direction (b) For WB Direction



(c) For SB Direction (d) For NB Direction

Figure 5-9 PCS counts vs. SL Index fitted regression model using hourly volumes (Scenario 1)

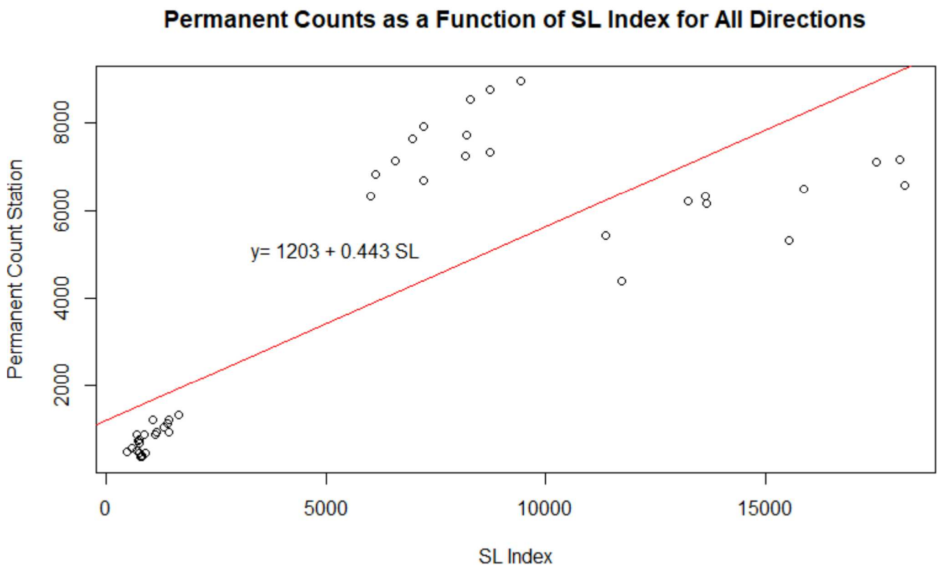
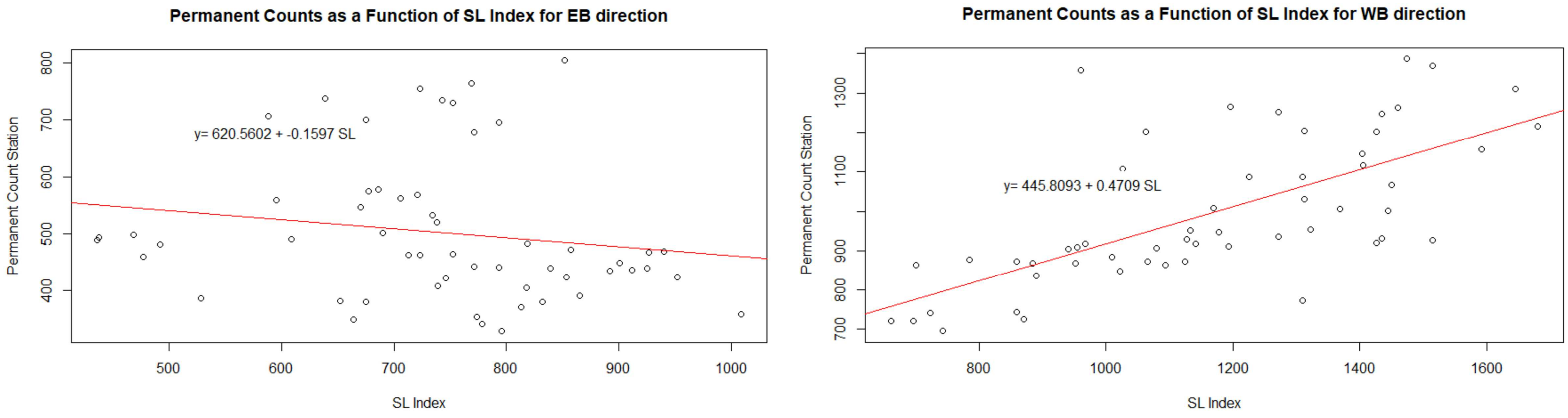


Figure 5-10 PCS counts vs. SL Index fitted regression model for all directions using hourly volumes (Scenario 1)

In the second variation (Scenario 2), the hourly volume data for every weekday is averaged over the whole month from 4:00 to 5:00 PM, resulting in a total of 55 data points for the training dataset. The reason weekdays (Monday through Friday) are chosen to perform this analysis is to observe the change in the SL Index data when a larger dataset is considered. Again, the fitted regression models did not exhibit good performance

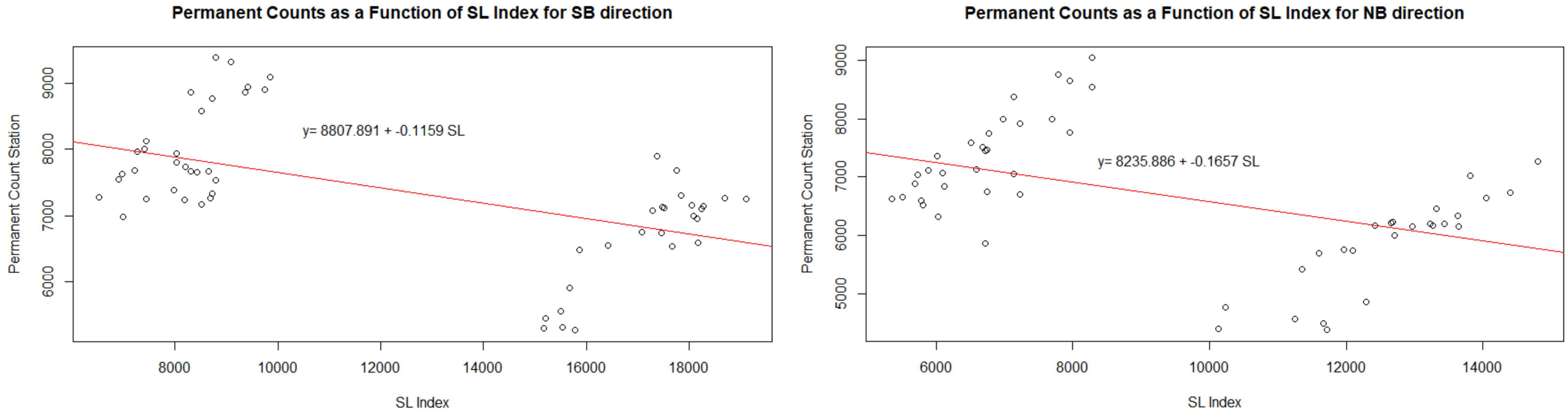
Table 5-8 Regression statistical inferences for PCS counts as a function of SL Index for weekday average peak hour

Direction	Regression Equation	R^2	p-value
EB	PCS = 620.5602 – 0.1597SL	2.9%	0.220
WB	PCS = 445.8093 + 0.4709SL	46.3%	0.000
SB	PCS = 8807.8910 – 0.1159SL	29.0%	0.000
NB	PCS = 8235.8860 – 0.1657SL	22.0%	0.000
All Directions	PCS = 1256.0000 + 0.447SL	62.8%	0.000



(a) For EB Direction

(b) For WB Direction



(c) For SB Direction

(d) For NB Direction

Figure 5-11 PCS counts vs. SL Index fitted regression model using hourly volumes (Scenario 2)

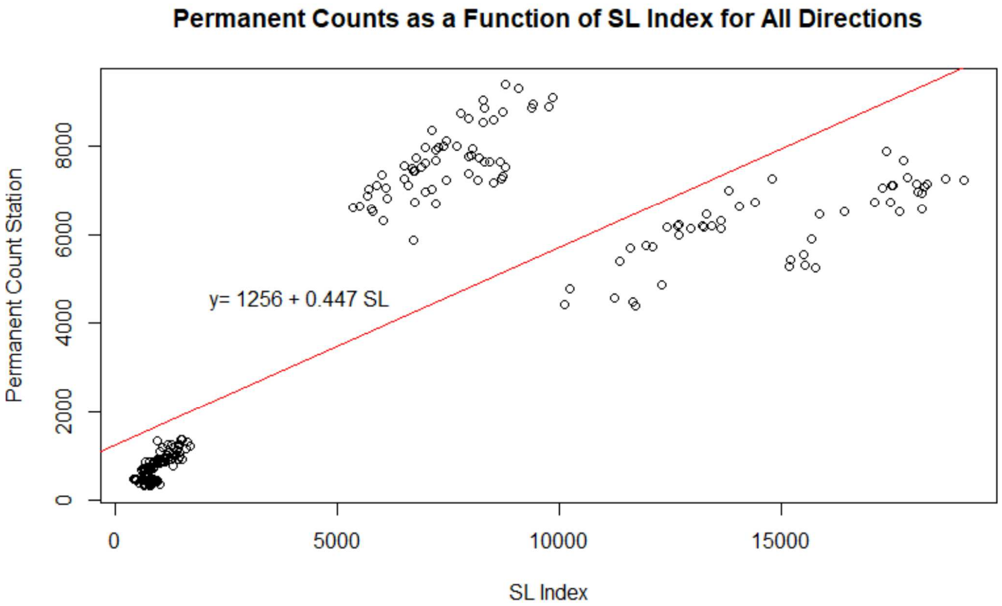
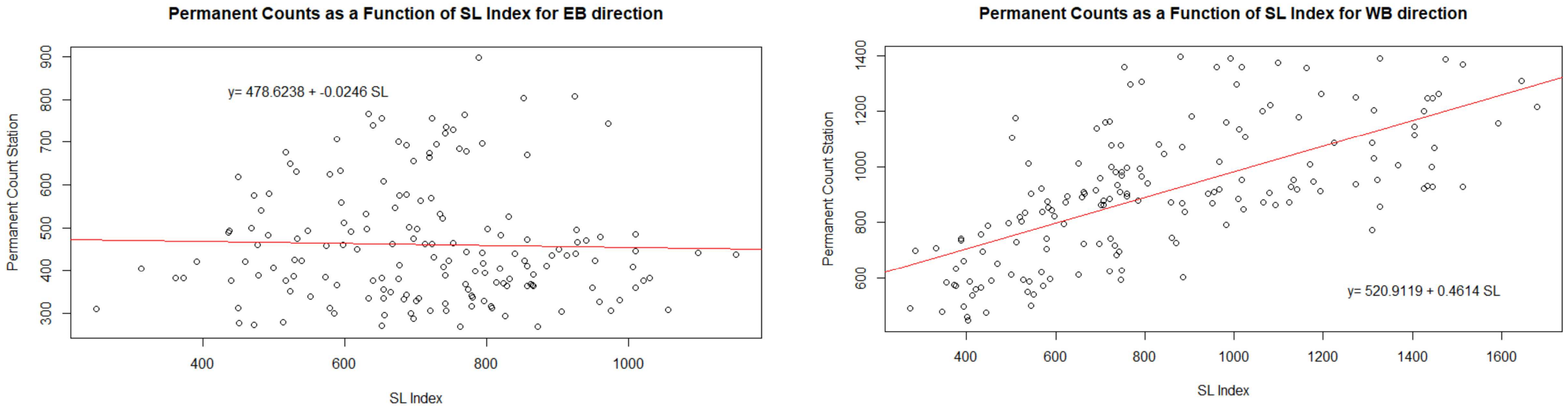


Figure 5-12 PCS counts vs. SL Index fitted regression model for all directions using hourly volumes (Scenario 2)

In the third variation (Scenario 3), the analysis period is increased by two hours from the previous scenario to capture more of the peak period. As a result, the weekdays (Monday through Friday) are averaged over the whole month from 4:00 to 7:00 PM, resulting in a total of 165 data (5 days, 3-hour slots, and 11 months) points for the training dataset. As was the case with the other two variations, the fitted regression models did not exhibit good performance.

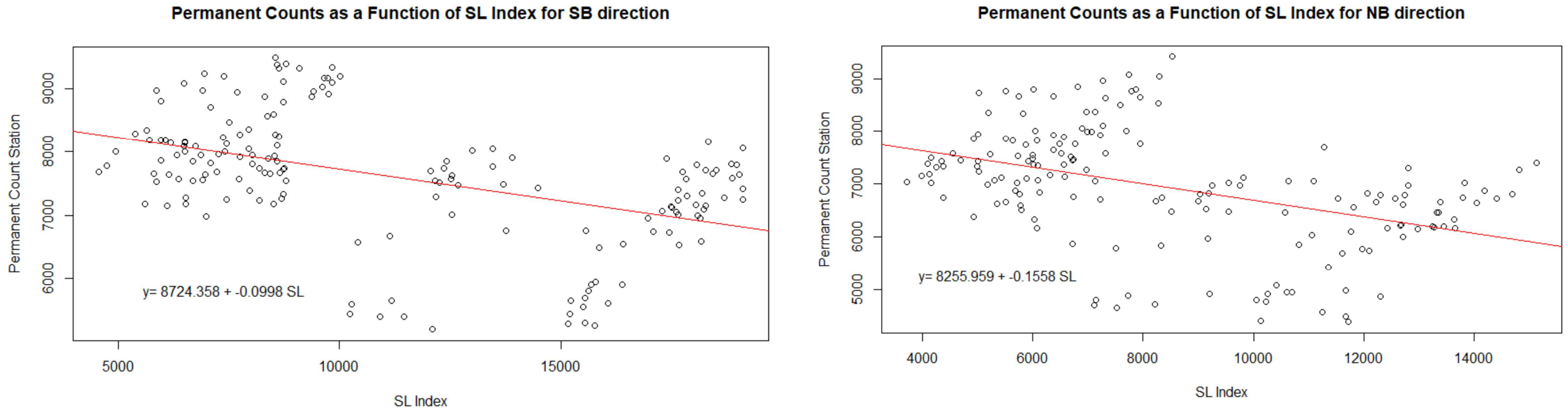
Table 5-9 Regression statistical inferences for PCS counts as a function of SL Index for weekday average <u>peak period</u>

Direction	Regression Equation	R^2	p-value
EB	PCS = 478.6238 – 0.0246SL	0.1%	0.700
WB	PCS = 520.9119 + 0.4614SL	43.0%	0.000
SB	PCS = 8724.3580 – 0.0998SL	21.1%	0.000
NB	PCS = 8255.9590 – 0.1558SL	18.6%	0.000
All Directions	PCS = 1359.0 + 0.493SL	61.4%	0.000



(a) For EB Direction

(b) For WB Direction



(c) For SB Direction

(d) For NB Direction

Figure 5-13 PCS counts vs. SL Index fitted regression model using hourly volumes (Scenario 3)

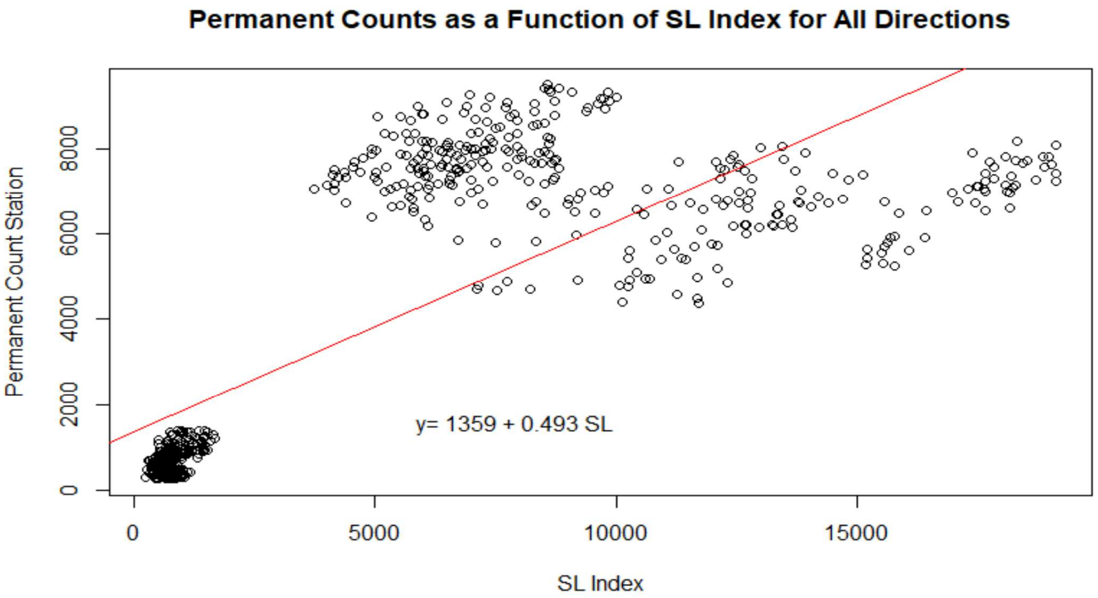


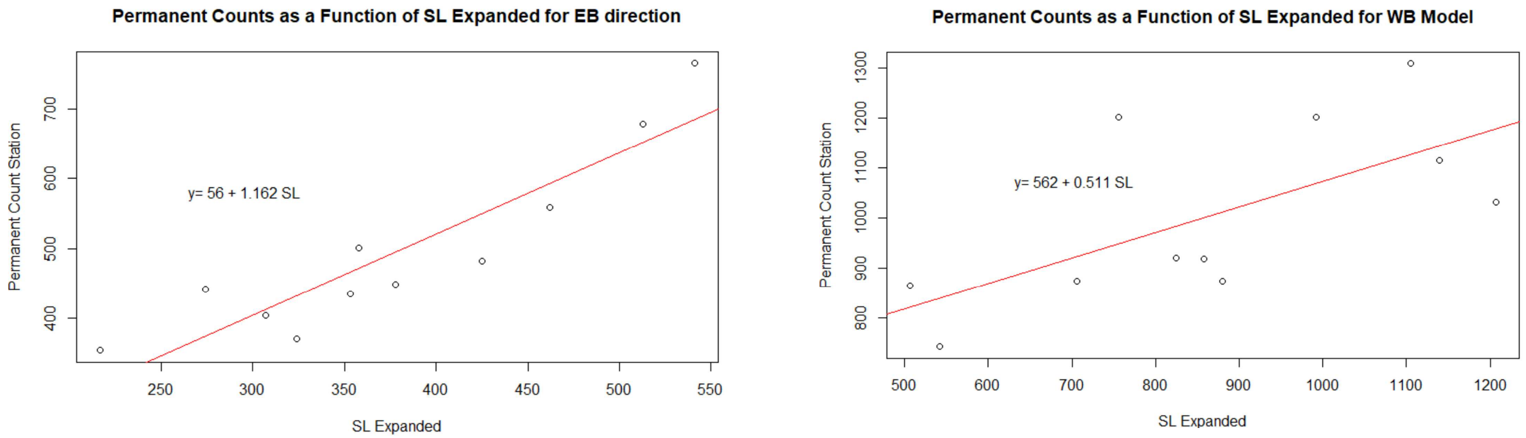
Figure 5-14 PCS counts vs. SL Index fitted regression model for all directions using hourly volumes (Scenario 3)

5.4.6 Estimating Hourly Volume at PCS locations Using Regression Analysis based on SL Expanded Volumes

Given the poor prediction of the regression model between the hourly SL Index and hourly PCS, additional exploration is done this time to base the prediction on the hourly output of SL Expanded volumes corrected based on local data. Regression models were developed between the hourly SL Expanded volumes and PCS hourly volumes. The SL and PCS volume data are divided into training datasets, consisting of data for 11 months, and testing dataset, consisting of data in the remaining (one) month. The PCS values are used as the response or dependent variable, and the SL Expanded volumes are used as the explanatory or independent variable. The utilized data is in the form of hourly data for every day of the week, averaged over the whole month, resulting in seven data points for every hour in every month. Similar to the previous regression models, PCS hourly data for every day of the week is manually averaged over the whole month and used as the response variable. As is done in the previous section, this study tried three different variations of the regression models using the hourly volume data. The All-Direction model appears to provide a good fit to the data. Regression plots and models are shown in Figure 5-15 and Figure 5-16 for further inferences.

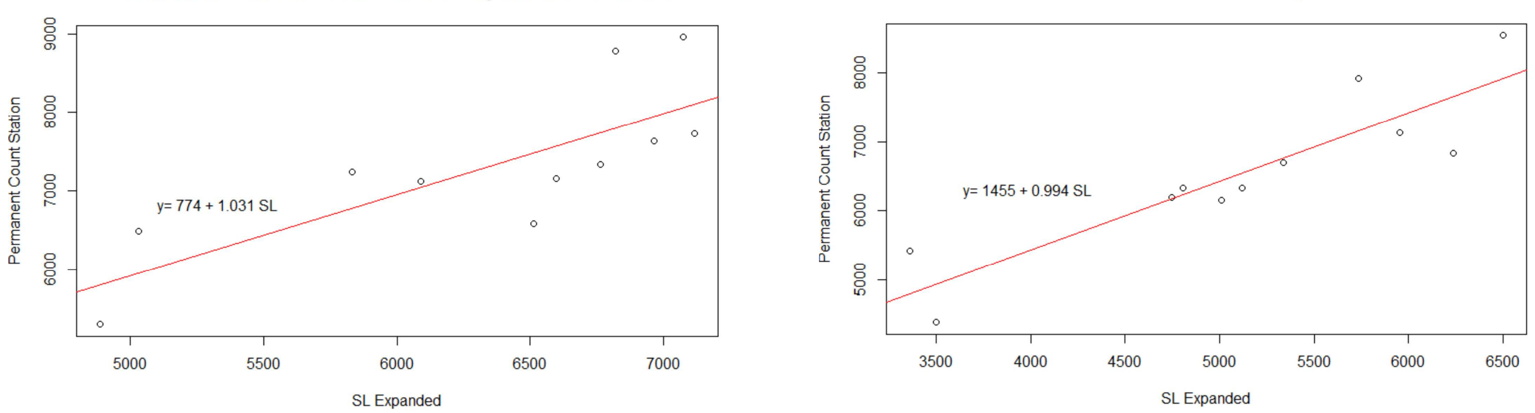
Table 5-10 Regression statistical inferences for PCS counts as a function of SL Expanded volumes for Tuesday peak hour

Direction	Regression Equation	R^2	p-value
EB	PCS = 56.0 + 1.162SL	83.1%	0.000
WB	PCS = 562.0 + 0.511SL	43.6%	0.027
SB	PCS = 774.0+1.031SL	62.9%	0.004
NB	PCS = 1455.0 + 0.994SL	80.0%	0.000
All Directions	PCS = 86.0+ 1.181SL	97.7%	0.000



(a) For EB Direction

(b) For WB Direction



(c) For SB Direction

(d) For NB Direction

Figure 5-15 PCS counts vs. SL Expanded fitted regression model using hourly volumes (Scenario 1)

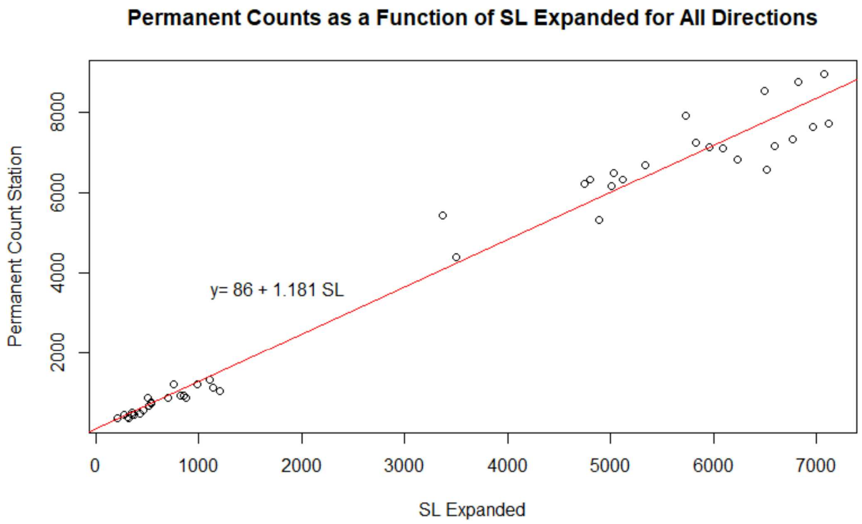
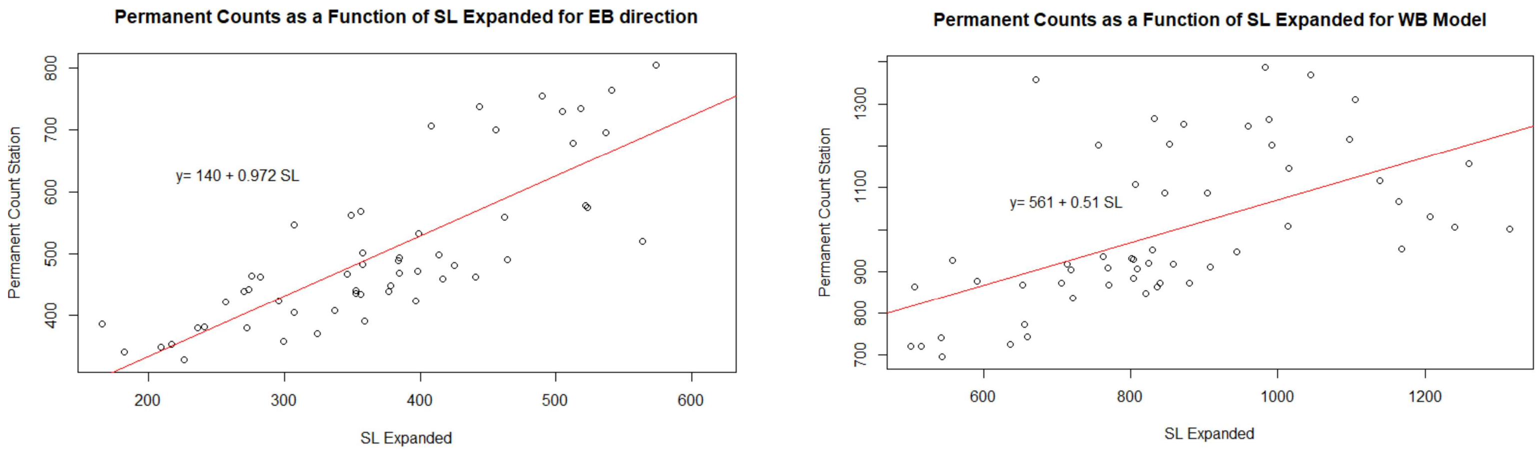


Figure 5-16 PCS counts vs. SL Expanded fitted regression model for all directions using hourly volumes (Scenario 1)

As shown in Table 5-11 and Table 5-12 similar pattern of R^2 values were obtained when conducting the regression analysis based on the hourly SL Expanded volumes using weekday average peak hour and weekday average peak period volumes. Regression plots and models for Scenario 2 and Scenario 3 are shown in Figure 5-17, Figure 5-18,
Figure 5-19 and Figure 5-20 for further inferences.

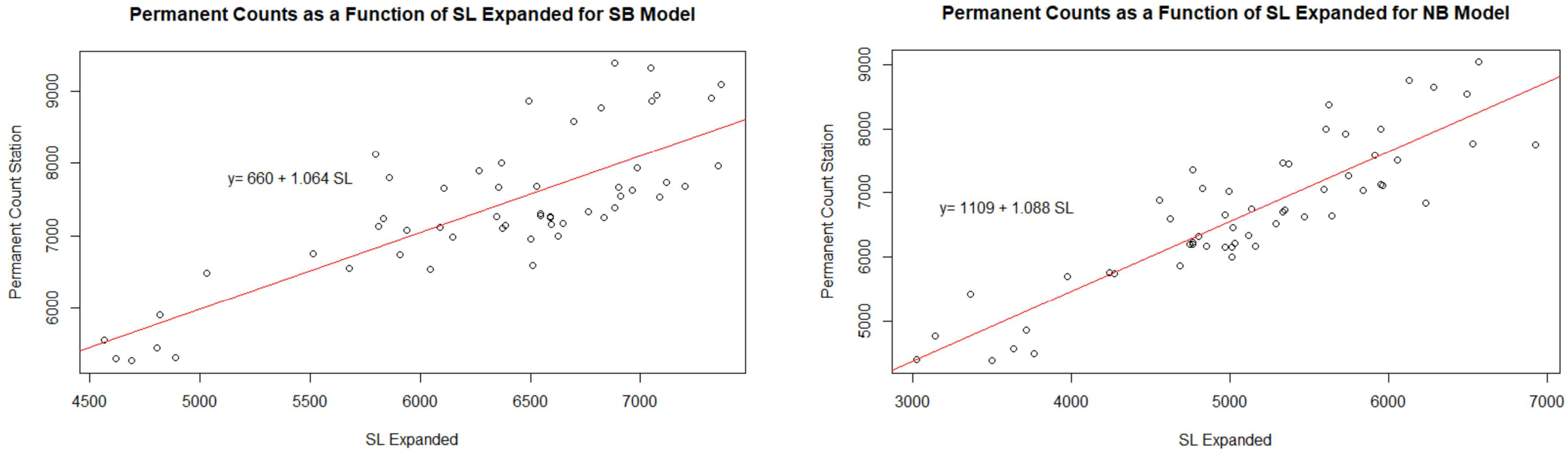
Table 5-11 Regression statistical inferences for PCS counts as a function of SL Expanded volumes for weekday average peak hour

Direction	Regression Equation	R^2	p-value
EB	PCS = 140.0 + 0.972SL	63.5%	0.000
WB	PCS = 561.0 + 0.51SL	32.2%	0.000
SB	PCS = 660.0+ 1.064SL	63.5%	0.000
NB	PCS = 1109.0 + 1.088SL	78.1%	0.000
All Directions	PCS = 78.0+ 1.204SL	97.7%	0.000



(a) For EB Direction

(b) For WB Direction



(c) For SB Direction

(d) For NB Direction

Figure 5-17 PCS counts vs. SL Expanded fitted regression model using hourly volumes (Scenario 2)

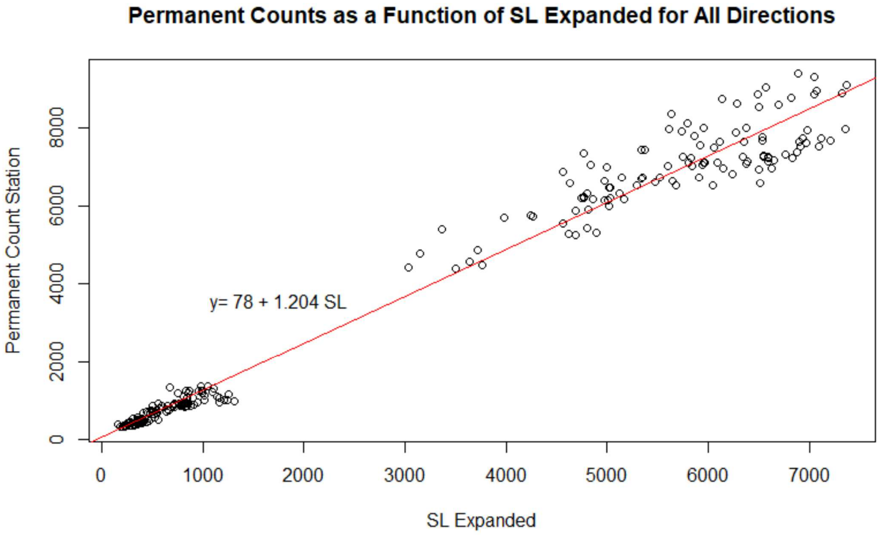
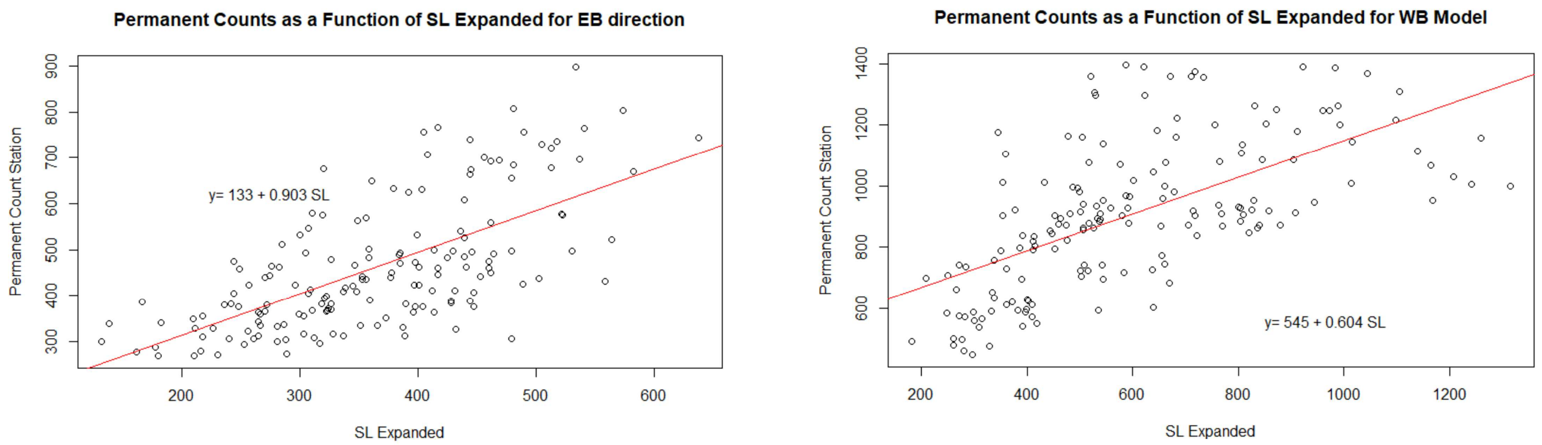


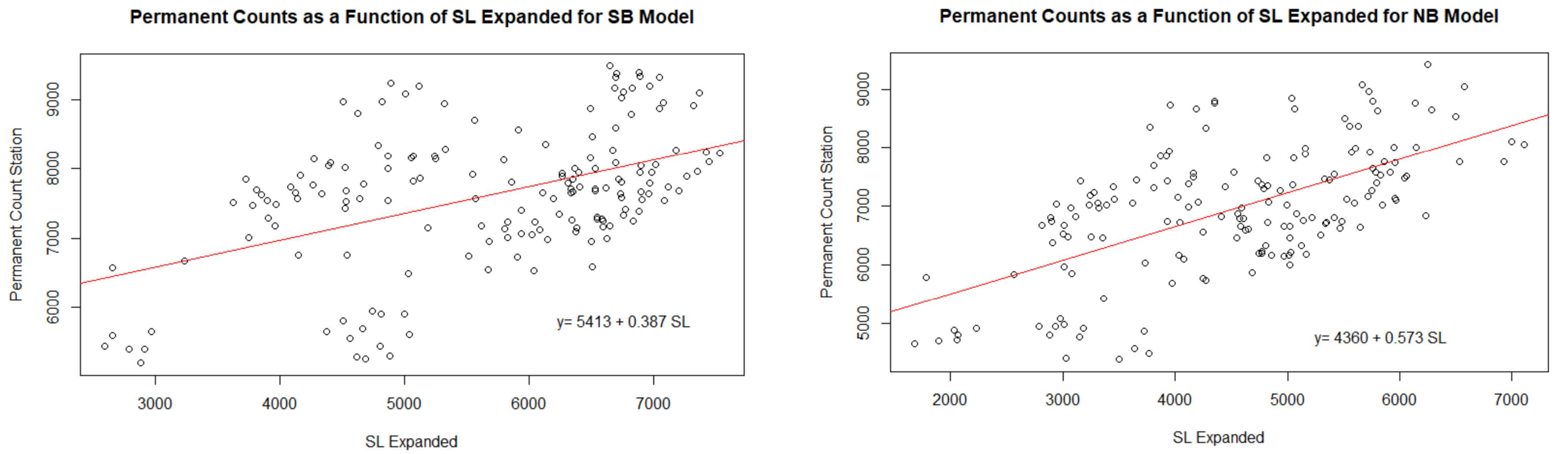
Figure 5-18 PCS counts vs. SL Expanded fitted regression model for all directions using hourly volumes (Scenario 2)

Table 5-12 Regression statistical inferences for PCS counts as a function of SL Expanded volumes for weekday average <u>peak period</u>

Direction	Regression Equation	R^2	p-value
EB	PCS = 133.0+ 0.903SL	42.8%	0.000
WB	PCS = 545.0 + 0.604SL	38.8%	0.000
SB	PCS = 5413.0 + 0.387SL	22.8%	0.000
NB	PCS = 4360.0 + 0.573SL	37.9%	0.000
All Directions	PCS = 370.0+ 1.298SL	90.7%	0.000



(a) For EB Direction **(b) For WB Direction**



(c) For SB Direction **(d) For NB Direction**

Figure 5-19 PCS counts vs. SL Expanded fitted regression model using hourly volumes (Scenario 3)

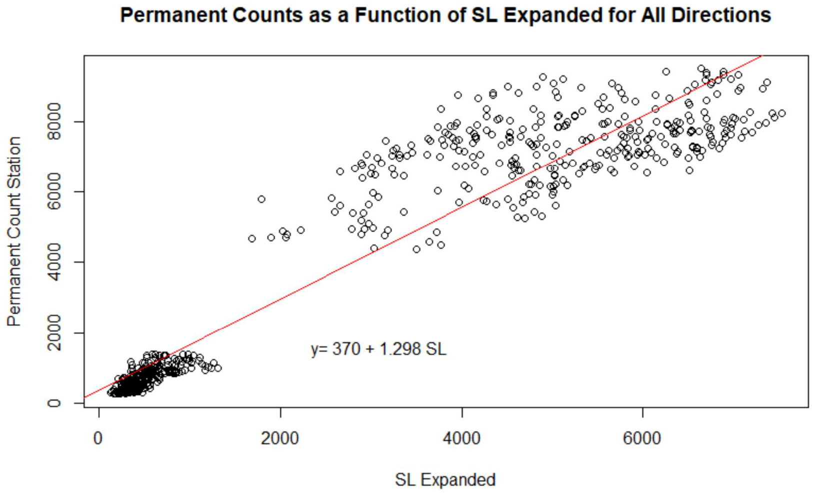


Figure 5-20 PCS vs. SL Expanded fitted regression model for all directions using hourly volumes (Scenario 3)

Based on the statistical results, the accuracy of the hourly volume estimation based on the regression model selected for the Tuesday Peak Hour (Scenario 1 of the SL Expanded models) was selected for comparison with the accuracy of the default SL Expanded data. The MAPE values of the models reported in Table 5-13 indicate how close the developed models are to the real-world data collected from the PCS. It is evident that all regression models developed for hourly volumes produced large errors in volume estimation. One should also remember that this evaluation is done to estimate the error in volume estimations at the same location where the PCS are located. For the models to be useful, they should be transferable and produce acceptable results for locations other than the PCS location. This is expected to be more difficult than estimating the volumes at the PCS location.

Table 5-13 MAPE of different regression models for hourly volume estimation

Used Model	**Measure**	**Flagler Bridge EB**	**Flagler Bridge WB**	**I-95 NB**	**I-95 SB**
SL Expanded Hourly Aggregation	MAPE Training Data	23.65%	17.65%	21.86%	12.82%
	MAPE Testing Data	40.00%	43.00%	32.00%	27.00%
Direction Specific Linear Regression based on SL Expanded (Tuesday Peak Hour)	MAPE: Training Data	9.52%	10.80%	6.08%	7.27%
	MAPE: Testing Data	22.00%	23.00%	8.00%	10.01%
All-Direction Linear Regression based on SL Expanded (Tuesday Peak Hour)	MAPE: Training Data	11.42%	18.49%	8.83%	8.88%
	MAPE: Testing Data	17.00%	25.00%	18.00%	13.00%

5.4.7 Summary

The results presented in this chapter indicate that there are significant discrepancies between the AADT and MADT estimated based on the SL Expanded volume data and the PCS data used as ground truth data for the two locations. Large errors were also found when estimating the seasonal factors based on the SL data.

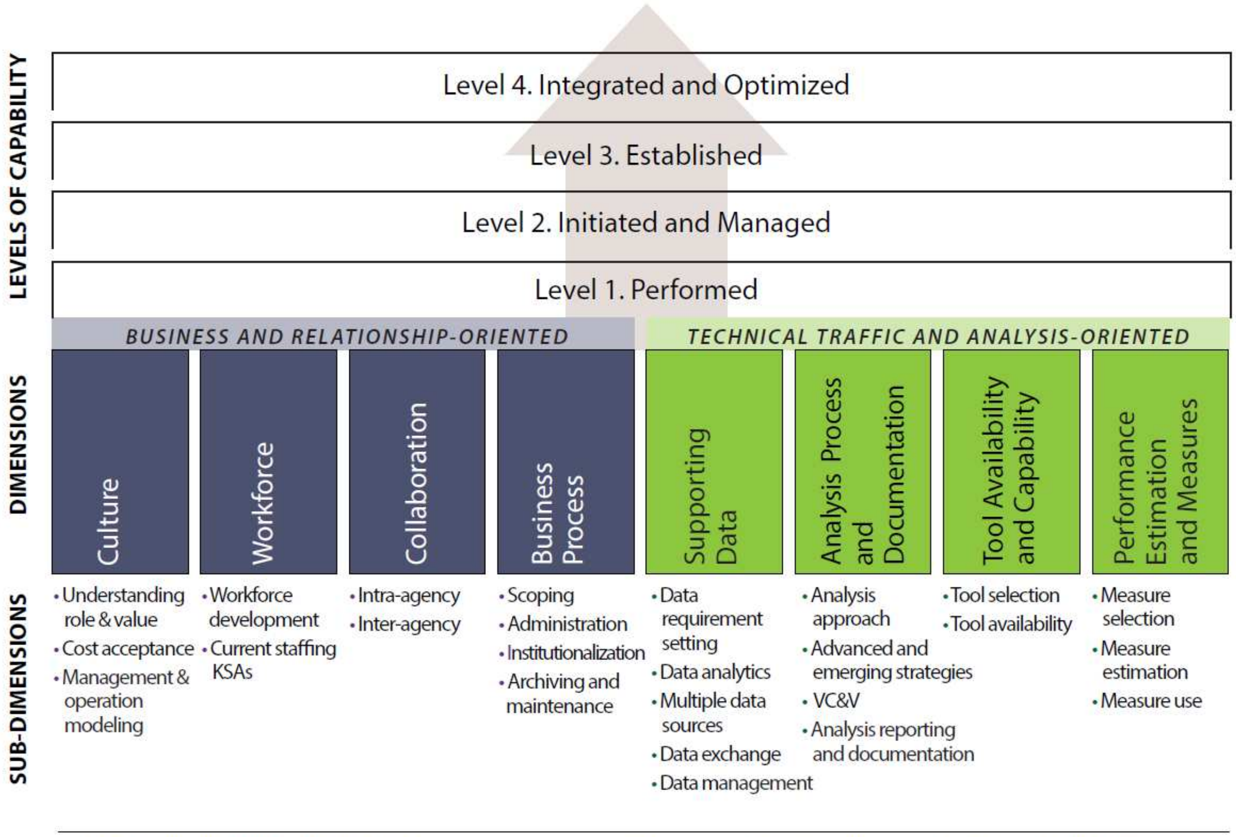
Considering the results above, this study investigated and refined the volume estimation based on SL data by developing regression models that relate the SL data to the ground truth PCS data. These models were then investigated for use to expand the SL data rather than using the SL Expanded data. The results from the regression analysis indicate that statistically significant relationships could be obtained between the PCS daily counts and SL Index. Overall, the regression models between the PCS counts and the SL Expanded daily volumes were less significant that those between the PCS counts and the SL Index. The use of the regression models based on the SL Index produced a MAPE of 5.35% to 8.14% for I-95 daily counts and 7.40% to 12.88% for the Flagler Bridge daily counts. Depending on the specific applications, these errors may or may not be acceptable. The above results indicate that the development of regression models between PCS data and SL data has the potential of providing acceptable results for daily volume estimation, particularly for higher volume segments. However, it should be remembered that the testing here is done using PCS Count and SL Index data from the same location from which the data is collect from for the regression. For the models to be useful, they need to be tested to estimate the volumes for locations other than the locations of the PCS station used in the regression. Such testing should be done in a future study. It is evident that all regression models between the PCS counts and SL data, developed in this study for hourly volumes, produced large errors in volume estimation.

CHAPTER 6: EXPLORING THE DEVELOPMENT OF MICROSIMULATION CLEARINGHOUSE PRACTICES

6.1 INTRODUCTION

This chapter reports on the results of Task 5 of the project. The objective of this task is to define the needs of the FDOT in traffic simulation training. Training is needed to build a robust workforce within the FDOT and its public sector partners and consultant, which is needed to maintain and advance traffic analysis and simulation capabilities. Currently, there is a limited Department sponsored training for micro-simulation and multiresolution modeling training. This document recommends a unified approach to address Department needs.

A recent FHWA has developed a capability maturity framework (CMF) for transportation agencies to assess their traffic analysis and simulation capabilities and to identify the potential steps for the agency to take to advance to the next level of capability based on the needs and priorities of the agency (Hadi et al. forthcoming). The framework categorized the capabilities in eight major dimensions and 25 sub-dimensions related to these eight dimensions. The framework allows the ranking of the capability of the agency in one of four levels of maturity for each dimension. These dimensions and subdimensions of the capabilities identified in the above-mentioned project are used in this study as a basis for identifying the training needs to advance the capabilities. Figure 6-1 illustrates the eight dimensions comprised of 25 sub-dimensions and the four different levels of capability within the fundamental dimensions of traffic analysis. Four of the dimensions are categorized as business and relation oriented including the Culture, Workforce, Collaboration, and Business Process. The remaining dimensions are categorized as Technical Traffic and Analysis including Supporting Data, Analysis Process and Documentation, Tool Availability and Capability, and Performance Estimation and Measures. The needed capabilities to go from a lower level to a higher level in the eight dimensions were used as a major consideration when setting the training approach in this document. An additional important input to setting the training approach is the information obtained in Task 1 (see Chapter 2) of this project that identified the current state and needs of traffic simulation in Florida.



KSAs - knowledge, skills, and abilities, TSMO - transportation system and management, VC&V - verification, calibration, and validation

Source: FHWA.

TSMO = transportation systems management and operations. VC&V = verification, calibration, and validation.

Figure 6-1 Illustration. Overall traffic analysis capability maturity framework.

6.2 UTLIZED DOCUMENTATION

The following documents were used as resources in this task. In addition, this task uses information obtained in previous tasks of this project.

1) *Traffic Analysis Handbook*. Florida: Florida Department of Transportation - Systems Planning Office, FDOT, Tallahassee, FL 2021.
2) Hadi, M., S. Shabanian, H. Ozen, Y. Xiao, M. Doherty, C. Segovia, and H. Ham. 2014. *Application of Dynamic Traffic Assignment to Advanced Managed Lane Modeling*. Prepared for FDOT Research Center, Final Research Report, Prepared for FDOT Research Center, January 2014.
3) Hadi, M., D. Mitchell, D. Hale, R. Hurtado, "Traffic Analysis Capability Maturity Framework," Report Produced for the Federal Highway Administration (FHWA), Forthcoming.
4) Hadi, M., Xiao, Y., Wang, T., Fakharian Qom, S., Azizi, L., Jia, J., A. Massahi, S. Iqbal. 2016. *Framework for Multi-Resolution Analyses of Advanced Traffic Management*

Strategies. Final Report. Prepared for Florida Department of Transportation, November, 2016

5) List, G. at al. “Transportation System Simulation Manual,” Transportation Research Board, Forthcoming.
6) Mahmassani, H.S., Elfar, A., Shladover, S., and Huang, Z. 2018. Development of an Analysis/Modeling/Simulation (AMS) Framework for V2I and Connected/Automated Vehicle Environment Final Report – October 18, 2018 FHWA-JPO-18-725.
7) Sloboden, J., Lewis, J., Alexiadis, V., Chiu, Y. and Nava. E. 2012. *Traffic Analysis Toolbox Volume XIV: Guidebook on the Utilization of Dynamic Traffic Assignment in Modeling.* Washington, DC: FHWA.
8) Wunderlich, K. E., Alexiadis, V., & Wang, P. 2017. *Scoping and Conducting Data-Driven 21st Century Transportation System Analyses* (No. FHWA-HOP-16-072). United States. FHWA. Office of Operations.
9) Wunderlich, K. E., Vasudevan, M., & Wang, P. 2019. Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Modeling Software. Update to the 2004 ed. Washington, DC: U.S. Department of Transportation – FHWA.

6.3 Training Needs

As stated earlier, this study identifies the needs for the traffic simulation training program based on identified needs for the training using information gathered in previous tasks in addition to the information provided in the FHWA “Traffic Analysis Capability Maturity Model Framework”. The followings are the identified needs.

1. There is a need for the Department’s decision makers and upper managers to have technical understanding of the roles and values of simulation, the needs to build capability at different levels within the agency, and the needs for spending the appropriate funding and time to build simulation models to support different business processes,

2. The training program should emphasize the importance of interagency and intra-agency collaboration in building the capability and conducting projects in traffic simulation.

3. There is a need to train decision makers on procedures to evaluate and select teams for simulation projects such as qualifications, cost, project experience, and project management capability.

4. There is a need to train project managers and senior personnel on the scoping of traffic simulation projects to consider various aspects and issues that need to be considered in the planning and scoping for the simulation projects.

5. There is a need to provide training on how to identify the data needs, availability, quality, and consistency of data and how to archive, process, and share the data for use in traffic simulation modeling tasks.

6. There is a need for the traffic simulation modelers to understand the theory of macroscopic and microscopic simulation modeling such as the fundamental macroscopic functions, car followings, lane changing, and gap acceptance.

7. Traffic simulation modelers and project managers need to understand the basic concepts of simulation in general and traffic simulation in particular including the different types of simulation models.

8. Traffic simulation modelers and project managers how to develop and provide inputs to simulation models.

9. Traffic simulation modelers need to understand the concepts and applications of dynamic traffic assignment and multiresolution modeling.

10. Traffic simulation modelers need to understand the use of multiscenario analysis for certain applications.

11. There is a need to introduce traffic simulation modelers to multi-modal simulation including transit, pedestrians, freights, and bicycles.

12. There is a need to train simulation modelers to simulate transportation system and management (TSM&O) including managed lanes and other active traffic and demand managements.

13. There is a need to introduce simulation modelers to guidance and methods of simulating advanced vehicle technologies including connected, automated, connected automated, cooperatives, electric and shared vehicles.

14. There is a need to provide an introduction to dynamic traffic assignment (DTA) concepts and applications including a description of DTA, the importance of DTA, and how to develop and use successful DTA models.

15. Simulation modelers need to learn how to perform the verification, calibration, and validation (VC&V) of simulation models based on FDOT guidance and recent findings from national efforts on the subject.

16. Project managers and simulation modelers need to understand how to best utilize simulation model results in combination with other types of analysis and visualization techniques to support agency's decision.

17. There is a need to train agency staff that are responsible for checking the quality of simulation projects on techniques and best practices for traffic simulation model review.

18. There is a need for simulation modelers to understand statistical concepts and applications for use in data and simulation model output analyses.

6.4 Potential Training Workshops

As stated earlier, this study identifies a traffic simulation training program based on identified needs for the training using information gathered in previous tasks in addition to the information provided in the FHWA "Traffic Analysis Capability Maturity Model Framework". The followings workshops were identified in this study to address the training needs.

- Traffic Simulation for Decision Makers
- Traffic Simulation Project Scoping and Procurement
- Supporting Data for Traffic Simulation
- Traffic Flow Theory and Characteristics
- Basic Traffic Simulation Concepts and Applications
- Advanced Traffic Simulation Concepts and Development
- Modeling Advanced Vehicle Technologies
- Dynamic Traffic Assignment
- Simulation Model Verification, Calibration and Validation
- Reporting and Utilization of Traffic Simulation Results
- Simulation Model Review/Quality Checking
- Statistical Analysis for Traffic Simulation

The following subsections provides the following information for each of the workshop.

- Workshop Description
- Content
- Addressed Needs
- Supported Dimensions of the Capability Maturity
- Expected Outcomes
- Attendees’ levels
- Estimated Duration
- Constraints

6.4.1 Traffic Simulation for Decision Makers

Description: This module provides technical understanding of simulation modeling and its value in supporting agency’s decisions. It also addresses the funding and resources required to conduct simulation models and the importance of allocating appropriate funding and time to the simulation models.

The module also provides an understanding of the role of different analysis types at different points in project planning and development. To build the understanding, the module provides an overview of simulation modeling, data collection, use and applications of the appropriate analysis method and tools, calibration and validation of the models, and the requirements to review the models.

In addition, the module will discuss the importance of intra-agency and inter-agency collaboration in sharing resources, data, and workforce development.

Content:

- Overview of traffic simulation tools and applications – provide a basic level of simulation models an approach and how they are different from analytical/deterministic traffic analysis tools.
- Overview of traffic simulation model development – review at a high level how a simulation model is developed and calibrated to meet project needs.
- Understanding the role and value traffic simulation in supporting agency's business processes – provide a list of the business processes FDOT and partner agencies like the metropolitan organization (MPOs) that are supported and can be supported by simulation modeling and make the business case for utilization traffic simulation to support the processes.
- Understanding the cost and value of traffic simulation – point to the need of providing sufficient budget to conduct simulation modeling and provides information on the potential cost of simulation compared to the values that can be obtained using simulation.
- Intra-agency and interagency collaboration – emphasize the need for strong collaboration between different units within the same department, among different departments of an agency, and different agencies including clearly defined and integrated roles in this collaboration.
- Traffic simulation project procurement - discuss procedures to evaluate and select teams for simulation projects such as qualifications, cost, project experience, and project management capability.

Addressed Needs: 1, 2, and 3

Supported Capability Maturity Dimensions: Culture, Collaboration, and Business Process dimensions.

Attendees Level: Decision makers and project managers

Estimated Duration: Four hours

Constraints: Additional research is needed to identify the value and cost of simulation models for different applications and best practices for procuring simulation models.

6.4.2 Traffic Simulation Project Scoping and Procurement

Description: This module will review the scoping of traffic simulation projects including defining project objectives and performance measures, data needs, selecting analysis approach and tool(s), and estimating costs and schedules. The scoping includes identifying the needed type, resolution, and temporal and spatial extents of the analysis.

Content:

- Setting analysis objectives and performance measures – provide understanding of how to identify the analysis objectives based on stakeholder inputs and the selection of performance measures that are related to each objective.
- Identification of data requirements and availability – describe how data should be considered when scoping simulation project including the recommendations provided in the deliverable of the FHWA's Scoping and Conducting Data-Driven 21st Century Transportation System Analyses (Wunderlich et al. 2017).
- Temporal and spatial extent – explain the requirements and methodology of setting the geographical and temporal limits to the analysis.
- Selecting analysis approach and tools– Identify the options for demand, supply, and operation modeling for existing and future analysis years and how to select the analysis approach and tools considering the identified project analysis approach, needs, requirements, and constraints.
- Identifying modeled scenario – discuss the decision to need to scope various recurrent conditions and non-recurrent conditions (incident events, weather events, and work zone conditions) based on project needs.
- Verification, calibration, and validation (VCV) methodology – describe the specification of standards, guidance, and or VCV methodology in the scooping process.
- Review process – explain how the review process can be specified in the scoping.
- Budget and schedule identification – review parameters that can be used to identify adequate budget and schedule for the project.
- Potential risk identification and mitigation – identify risks that can impact the product quality, schedule, and cost.

Addressed Needs: 4.

Supported Capability Maturity Dimension: Business Process

Staff Level: Project manager and senior modelers

Estimated Duration: Four hours

Constraints: Additional research is needed to identify the value and cost of simulation models for different applications and best practices for procuring simulation models.

6.4.3 Supporting Data for Traffic Simulation

Description: This module focuses on identifying the needs, availability, quality, and consistency of data for use in developing, calibrating, and validating simulation models. This model reviews the use of data from multiple sources, including existing and emerging technologies, to satisfy AMS data needs This module also discusses data management and sharing and the use of data analytics and visualization to support and complement traffic simulation to achieve project objectives.

Content:

- Identifying the data requirements
    - Geometric data.
    - Traffic count data.
    - Traffic signal operations data.
    - Calibration data.
    - Safety data.
    - Incident, weather and construction data
- Data resolution – specifies the needed temporal and spatial resolutions of various data elements
- Filling the data gaps – review collecting and fusing data from multiple sources based on data requirements including data from emerging technologies and high-resolution data obtained from high-resolution sensors/controllers, vehicle trajectories from drones, and connected automated vehicles
- Data quality– define and provide methods to examine the data completeness and quality
- Data filtering and correction techniques – identify methods for data filtering and correction considering the identified data quality and temporal and spatial inconsistencies in the data

- Challenges in estimating demands from counts – provide methods for estimating demands from traffic counts under uncongested conditions, recognizing the difficulty in doing so under certain conditions

- Utilization data analytics – Review methods and applications that utilize advanced data analytics and visualization techniques to support and complement simulation modeling development and calibration

- Data management, sharing, and governance – Review concepts to allow effective archiving and sharing of the data

Addressed Needs: 5.

Supported Capability Maturity Dimension: Supporting Data

Staff Level: Project manager and simulation modelers.

Estimated Duration: Six hours

Constraints: There is still a lot to be learned and researched related to the requirements and use of data for simulation modeling and the available guidance is not sufficient for this purpose.

6.4.4 Traffic Flow Theory and Characteristics

This module will review macroscopic and microscopic traffic flow theory and concepts. The module will review the fundamental macroscopic parameters and relationships. In addition, the module will review microscopic parameters and relationships including car following, lane changing, and gap acceptance.

Content:

- Traffic parameters – review the fundamental macroscopic and microscopic traffic parameters including the traffic flow rate, density, speed, time headway, and distance headway

- Macroscopic models – review of developed fundamental macroscopic traffic flow relationships (fundamental diagram, also called equilibrium or steady-state models) and dynamic models including shockwave theory that extends the fundamental relationship to model traffic dynamics in space and time

- Capacity and demand stochasticity – discuss the stochasticity in capacity and demand and how such stochasticity impacts traffic analysis, modeling, and simulation

- Bottleneck identification – present methods for identifying bottleneck locations and attributes

- Car following – explain the categories of car following models and describe car following models including early models and models currently used in existing traffic simulation tools

- Lane changing - explain the categories of car following models and describe car following models including early models and models currently used in existing traffic simulation tools

- Gap acceptance – discuss gap acceptance models and provide examples

Addressed Needs: 6

Supported Capability Maturity Dimension: Analysis Approach

Staff Level: Simulation modelers

Estimated Duration: Eight hours

Constraints: None.

6.4.5 Basic Traffic Simulation Concepts and Development

Description: This module reviews different types of traffic simulation models (macroscopic, microscopic, and mesoscopic models and their use. The module will then discuss approaches to conducting traffic analysis including to satisfy analysis requirements including advanced topics such as modeling TSM&O, managed lanes, multiple resolutions, multiple travel modes, and multiple operating condition simulation.

Contents:

- Simulation versus analytic analyses – make a distinction between analytical/deterministic tools like those that are based on the Highway Capacity Manual (HCM) procedures and simulation modeling and explain the applicability of each to different analyzed conditions

- Basic simulation concepts – describe the basic concepts of simulation models including the basic elements to be coded in simulation, treatment of time (time-based vs. event-based), static vs. dynamic analysis, model stochasticity, warm-up and cool-down periods, and performance measure calculation

- Macroscopic simulation tools – define macroscopic simulation tools, describe the type of models used in the tool, review typical input parameters, and review typical outputs

- Mesoscopic simulation tools, inputs, and outputs - define mesoscopic simulation tools, describe the type of models used in the tool, review typical input parameters, and review typical outputs

- Microscopic simulation tools, inputs, and outputs - define microscopic simulation tools, describe the type of models used in the tool, review typical input parameters, and review typical outputs

- Dynamic traffic assignment – discuss basic concepts of dynamic traffic assignment and discuss its advantage compared to static assignment

- Latent demands – explain the importance of the consideration of latent demands and how they can be addressed

- Extending simulation modeling capabilities – explain the use of application programming interface (API) to extend simulation modeling capabilities and provide examples of this use

- Simulation model development – discuss how to develop and provide inputs to simulation models including:
    - Network development
    - Geometry inputs:
    - Demand inputs
    - Driver and vehicle parameter inputs
    - Control and management inputs

Addressed Needs: 7 and 8

Supported Capability Maturity Dimension: Analysis Approach dimension and Tool Availability and Capability Dimension.

Staff Level: Project managers and simulation modelers

Estimated Duration: Six hours

Constraints: None.

6.4.6 Advanced Traffic Simulation Concepts and Applications

Description: This module reviews different types of traffic simulation models (macroscopic, microscopic, and mesoscopic models and their use. The module will then discuss approaches to conducting traffic analysis including to satisfy analysis requirements including advanced topics such as modeling TSM&O, managed lanes, multiple resolutions, multiple travel modes, and multiple operating condition simulation.

Contents:

- Multiresolution modeling – discuss how models of different levels can be linked in a forward and backward loop and in a hybrid simulation environment that run different resolutions of simulation in parallel

- Multiscenario modeling - review applications that benefit from multiscenario analysis and discuss how simulation can be conducted

- Multi-mode modeling – discuss the modeling of public transit, pedestrians, bicycles, freight, and other modes of transportation

- Modeling TSMO strategies – review the specific aspects of simulating TSM&O strategies such as ramp metering, adaptive signals, dynamic shoulder use, dynamic lane grouping, integrated corridor management, and so on. Present additional information regarding advanced concepts including real-time simulation, software-in-the-loop, and hardware-in-the-loop simulation

- Modeling managed lanes – discuss and review managed lane analysis and simulation based on the procedures presented in the FDOT 2021 Traffic Analysis Handbook.

Addressed Needs: 9 to 12

Supported Capability Maturity Dimension: Analysis Approach dimension and Tool Availability and Capability Dimension

Staff Level: Project managers and simulation modelers

Estimated Duration: 12-16 hours

Constraints: Additional research may be needed on multi-mode modeling

6.4.7 Modeling Advanced Vehicle Technologies

Description: This module reviews available framework, guidance, methods and models for simulating advanced vehicle technologies (ATV) including connected, automated, connected automated, cooperative driving, electric vehicles, and mobility as a service (MaaS). The modules focus on FDOT, and its partner needs to simulate ATV for planning and operations of highways with the presence of ATV. The module will include demonstration of the use of simulation to use cases that require assessing the traffic performance with ATV presence.

Contents:

- Review of ATV technologies and applications – provide basic knowledge of ATV technologies and applications and associated issues that can influence the modeling and simulation of these technologies such as forecasting market penetration, identification of the technologies on the traffic stream, etc.

- ATV modeling framework – discuss a framework for ATV analysis modeling that integrates the impacts of ATV on demands, supply, and operations.

- Scoping ATV simulation projects – discuss how the consideration of ATV impacts the planning and scoping of simulation projects including the identification of the objectives, hypotheses, data needs, data quality requirements, performance measures, responsible parties for various parts of the project, geographic and temporal scopes, studied alternatives, technical approach and appropriate analysis tools, and estimation of the required resource estimates.

- Data requirements for ATV modeling – review data requirements, availability, and methods for filling the data gaps for ATV simulation

- Considering uncertainty in ATV modeling – describe approaches that can be used to understand the uncertainties in ATV adoptions and impacts that influence their analysis, modeling, and simulation

- Using ATV simulation results – describe how ATV simulation modeling results can be used as part of the agency decision making processes considering ATV technologies and applications

Addressed Needs: 13

Supported Capability Maturity Dimension: Analysis Approach and Documentation dimension and Tool Availability and Capability dimension.

Staff Level: Project managers and simulation modelers

Estimated Duration: 4 to 6 hours

Constraints: Additional research needed on ATV modeling

6.4.8 Dynamic Traffic Assignment

Description: This module will provide an introduction to dynamic traffic assignment (DTA) concepts and applications including a description of DTA, the importance of DTA and where it can/should be applied, and successful applications of DTA. The module will also provide training related to the creation, validation/calibration, and convergence of DTA.

Contents:

- DTA concepts and components – describe what is DTA, how does DTA differ from conventional methods, the types and characteristics of DTA, and DTA components (time-dependent shortest path, assignment, loading) and associate approaches

- Why is DTA important - explain why is DTA important and its ability to provide temporal analysis of network conditions that consider important aspects such as buildup and dissipation of congestion, bottleneck impacts, peak spreading and flattening, etc.

- DTA project scoping – address particular aspects of DTA that need to be considered in scoping

- Identification of data requirements and availability – describe that the additional data requirements for DTA modeling

- Origin-Destination (O-D) matrix estimation – discuss methods for O-D estimation including available O-D matrix estimation (ODME) modules available in existing tools

- Verification, calibration, and validation – describe additional aspects of VCC related to DTA

- Convergence – provide the understanding necessary for the assignment convergence process, why ensuring convergence is important, and the criteria used for convergence assurance

- Links to activity-based models – review experiences with linking DTA with activity based models (ABM)

Addressed Needs: 14

Supported Capability Maturity Dimension: Analysis Approach and Documentation dimension

Staff Level: Project managers and simulation modelers

Estimated Duration: 6 hours

Constraints: None

6.4.9 Simulation Model Verification, Calibration, and Validation

Description: This module focuses on the verification, calibration, and validation (VC&V) of simulation models. The module will provide training on the FDOT VC&V guidance and recent findings from national efforts on the subject.

Contents:

- Definitions and concepts – define verification, calibration, and validation and point-out to the differences that these definitions are defined by different resources.

- Calibration metrics – discuss the selection of the calibration metrics for use in VCV tasks and model review to best indicate whether the performance estimations from simulation are correct, logical, and consistent with the performance estimated based on real-world data

- Simulation model verification process – describe the process to ensure that the simulation software can address all elements to be modeled and check that there are no error, missing information, inconsistency in the input data sets
- Simulation model calibration process – describe the calibration process including:
    - Identification of calibration targets including fixed and targets that vary depending on the model conditions
    - Identification of calibration methodology including the sequence of the calibration
    - Selection of the parameters to be fine-tune in the calibration
    - Selection of the performance measures to be used in the calibration
    - Identification of the method used for calculating the performance measures to ensure consistency between simulation and field data
    - Using statistical analysis and visualization in simulation model calibration.
- Simulation model validation process – describe the validation process including:
    - Creating or assembling the data sets to use for validation
    - Selection of the performance measures to be used in the validation and the method used in their calculations
    - Using statistical analysis and visualization in simulation model validation
- Vehicle trajectory utilization in calibration - describe the use of trajectories to calibrate mesoscopic and microscopic model parameters including path choice, lane choice, and car following

Addressed Needs: 15

Supported Capability Maturity Dimension: Analysis Approach and Documentation dimension

Staff Level: Project managers and simulation modelers

Estimated Duration: 12 hours

Constraints: There is still needs for significant research on the VCV methodology at the national and international levels.

6.4.10 Reporting and Utilization of Traffic Simulation Results

Description: This module discusses the utilization of simulation models to support agency's decision. It will discuss the performance metrics that are output or can be calculated by processing the output of simulation tools. These include mobility measures as well as non-traditional measures related to reliability, safety, sustainability, resilience, and equity. This module points out the importance of understanding the methods used to estimate a given metric using field data, highway capacity manual procedures, and various simulation tools that can be different, preventing direct comparison of these measures, The module will also decision how decisions can be made on simulation results including the use statistical analysis, visualization techniques, and sensitivity analysis. In addition, the module describes archiving the models and associated documentations for future use.

Contents:

- Performance measure selection – describe a process to select the best set of performance metrics that are related to the goals and objectives
- Performance measure calculation – point to the differences in the methods used to calculate measures based on field data and different tools, provide examples, and describe why understanding these differences are important
- Nontraditional measures – explain the use of simulation to estimate measures other than mobility measures such as safety, reliability, and pollutant emission
- Statistical analysis of simulation results – explain various statistical analysis and hypothesis testing that can be used to compare the performance of the evaluated alternatives
- Visualization of simulation results – describe best practices for the visualization of traffic simulation results
- Trajectory-based measures - explain how the modelers can use vehicle trajectories that are produced as outputs from simulation models to calculate performance metrics and why such calculations can be desirable in certain cases
- Utilization model outputs to support decision – review techniques that use simulation results in combination with other methods to support agency's decisions including benefit-cost analysis and multi-criteria decision analysis (MCDA)
- Documentation and reporting – identify best practices for the producing project documentation with sufficient levels of details to allow the review of the simulation modeling process, tasks, and results.
- Model archiving – describe procedures to archive the collected data, model inputs, model outputs, and project documentations for future use.

Addressed Needs: 16

Supported Capability Maturity Dimension: Business Process dimension and Analysis Approach and Documentation dimension

Staff Level: Project managers and simulation modelers

Estimated Duration: 6 hours

Constraints: None

6.4.11 Simulation Model Review/Quality Checking

Description: This module provides training on reviewing the products of simulation modeling projects to ensure the quality of these products. The review process is based on project documentations, model inputs, model outputs, dynamic animation, and visualization of model outputs

Contents:

- Project documentation Reviews – Identify aspects of the model process and results that needs to be documented in written project reports and how they can be reviewed
- Review of model inputs – describe the model input parameters that need to be reviewed and the acceptable ranges of parameters
- Review of model outputs– describe the model outputs that need to be reviewed and how to identify the correctness of these parameters
- Using visualization and dynamic animation – describe how to use visualization of model outputs and dynamic animation in the review process

Addressed Needs: 4 and 17

Supported Capability Maturity Dimension: Analysis Approach and Documentation dimension

Staff Level: Simulation model reviewers

Estimated Duration: 6 hours

Constraints: There is still no documented methodology or recognized best practice for simulation modeling review.

6.4.12 Statistical Analysis for Traffic Simulation

Description: This module provides training on the concepts and application of statistical analysis to support simulation modeling including probability distribution, hypothesis testing, regression analysis, and clustering analysis.

Contents:

- Statistical measures
- Probability distributions
- Confidence intervals and sample size
- Hypothesis testing
- Regression analysis
- Clustering analysis

Addressed Needs: 18

Supported Capability Maturity Dimension: Supporting Data dimension and Analysis Approach and Documentation dimension

Staff Level: Project managers and simulation modelers

Estimated Duration: 16 hours

Constraints: NA

CHAPTER 7: EXPLORING THE DEVELOPMENT OF MICROSIMULATION CLEARINGHOUSE PRACTICES

7.1 INTRODUCTION

One of the capabilities to enhanced traffic analysis, modeling, and simulation (AMS) practices is archiving and maintaining data, analysis files, and documents collected, used, and produced as part of AMS projects for future use by analysts, modelers, and researchers. This capability can increase the efficiency and quality and reduce the cost of the developed AMS models, in addition to providing information that may be lost for planning, design, and operations of the facility. In current practices, multiple AMS models have been developed for a location. After the project is done, modeling files are often lost and the modeling efforts that follow have difficulty or inability to locate and understand the files and the associated data and documentations.

The real-world data collected in previous projects can be very useful and reduce the required budget to collect data for other projects. In the worst case, it can be used as a reference to verify the quality of the newly collected data. In addition to the real-world data, the future modeling efforts will benefit from archiving the input and output files of the utilized tool in the analysis, summary of the main input and output performance measures in the analysis, any files resulting from further processing of the data and model outputs, and project documentations and deliverables. Archiving and maintaining data, performance measures, analysis files, and documents will also allow follow-up analyses to confirm the original analysis results and extending the analysis to conduct the analysis of additional alternatives and operational scenarios not conducted in the original project.

The development of microsimulation clearinghouse practices for AMS project archiving capability will ideally involve a documented and institutionalized process for archiving, sharing, using, updating, and maintaining data and archived files for future use. This Chapter reports on the results of Task 6 of the project. This Chapter provides recommendations for a standardized process for archiving, maintaining, and reusing the data, model, measures, and other deliverables of AMS projects. The Chapter recommends that the project team of a traffic simulation project develops a Data Management Plan (DMP) that complies with the process. The DMP will describe how the data and models of the analysis project will be generated, collected, managed, stored, protected, re-used, archived, and shared. Analysts that need to use the data and models in other efforts should be able to request these models for use in future projects and receive the data upon approval. It is expected that the FDOT will require any additional data collected and updates made to the original models in subsequent efforts to be submitted to the FDOT for incorporation into the archive.

Each DMP should provide sufficient information to locate, access, and use the data including:

- Description of the archived data, model, and documentation including the metadata, as outlined in Section 7.3
- Outline of the policies for data access and sharing process that comply with Section 7.4

- Documentation of the distribution and reuse policies of the archived and downloaded data, as described in Section 7.5 of this document.

- Document of the plan data archiving and preservation, as described in Section 7.6 of this document.

Section 7.2 of this document discuss the FDOT effort to develop Mobility Data Integration Space (MDIS) as it relates to the AMS archiving effort. This document recommends the consideration of MDIS for potential use in supporting the AMS data clearing house. Section 7.7 discusses a national effort to develop a common network specification, referred to as the General Modeling Network Specification (GMNS) to support sharing data and models associated with different levels of modeling. This specification may be useful for future FDOT efforts including potentially for a future version of the clearinghouse, as discussed in this document.

7.2 THE MOBILITY DATA INTEGRATION SPACE (MDIS)

MDIS is being developed by the Forecasting and Trends Office (FTO) of the FDOT to serve as an integrated environment of data from multiple sources. This data integration environment will facilitate data analysis and distribution and can be extended to archive the information that are recommended to be archived from AMS projects. The Next Generation FSUTMS effort of the FDOT has recognized the opportunity of using MDIS to archive and distribute the data required for the next generation of demand forecasting modeling in Florida. The vision, as outlined in the Next Generation Florida Standard Urban Transportation Modeling Structure (FSUTMS) white paper (FDOT, 2022b), is that MDIS will not only provide data from various sources to be used in the development of the demand models, but the system can be used to archive data generated from the models. This is in line in what is needed in this project (the FDOT Microsimulation: Department Assessment and Guidance project) in obtaining required data for simulation and archiving the data, inputs, and outputs of AMS projects. Thus, it is recommended that the development of the AMS data clearinghouse considers taking advantage of the FDOT development of MDIS and use the system as the clearinghouse platform.

The FSUTMS Next Generation white paper (FDOT, 2022b) provided examples of data housed in MDIS that can be used in demand forecasting model development including traffic counts, population, and employment. Another example given is the provision of control device, phasing, cycle time, and timing parameters information among other characteristics for each signalized intersection to support junction modeling in demand forecasting. The paper also provided examples of data generated by the models that can be stored in MDIS including future year traffic and congestion information.

The FSUTMS Next Generation white paper (FDOT, 2022b) recommends, at a minimum, establishing and maintaining a set of linking attributes to allow joining the FSUTMS datasets and other MDIS datasets. The examples given are segment IDs, station IDs, Census geographic IDs, as well as others. This would allow for seamless passing of data between the MDIS and FSUTMS datasets. The brief discussion of the use of MDIS to support the FSUTMS in the white paper points to the need to resolve the extents of the data items so that they align between datasets. The examples given are that it is not necessary that one highway link in the demand forecasting model corresponds to one roadway segment in MDIS or that one TAZ correspond to one Census Block Group in MDIS. The white paper states that it would be beneficial at a minimum that multiple links could be grouped into a single segment. The differences in the extent and resolution between the MDIS and AMS data will also be a challenge that needs to be resolved, if MDIS is used for AMS project archiving. Another example consideration in the FSUTMS Next Generation white paper is the possibility of converting specific model data into universal data types like standard database file (DBF) or comma-separated values (CSV) file formats that can be housed in a database to allow individuals who may not have access to the modeling software used to still review the model data. This also makes it easier to share data between models by removing the dependence on proprietary data formats. This is also recommended for the AMS clearinghouse recommended in this document. Although the input and output variables to simulation software are usually binary files in proprietary format, it is generally possible to write or have an API code to write the input and output measures in standard attribute specifications to a text, CSV, or DBF files that can be used and visualized, using commonly used data processing and visualization tools. Such files can be stored, in addition to the files used in the proprietary formats that can be used to run the model.

It is anticipated that initially the goal of the clearinghouse is to allow the users to download files and data associated with specific segments or zones. In this case, there will be a need use of standard metadata and also for standard attributes that link the files to data elements in the archive such links, zones, or subarea. However, if the requirement is to use input and output variables from AMS projects as attributes of the data elements in the dataset, then there will be a need for additional standardization of these variables and the associated schema. This standardization can be based on extension of the data specifications of MDIS, FSUTMS, the GMNS (reviewed later in this document), or combinations.

It is recognized that MDIS is a geographic information-based (GIS-based) system. Linking the variables in the simulation model with the variables in MDIS and FSUTMS spatially and temporarily will allow the use of these variables as GIS layers. Unfortunately, MDIS is currently an on-going effort and there are no documents beyond the mentioned Next Generation FSUTMS white paper to provide more information about the MDIS and associated data. Once such information become available, a future effort will need to provide more details about the potential integration of simulation data in MDIS. It is recommended that the FDOT will form a stakeholder group that involves public and private section simulation model users in Florida, the MDIS team, and the FDOT modeling and data leadership in early discussion to establish the AMS data clearinghouse with the potential use of MDIS of this project. It will also be very useful to identify at least one case study to demonstrate the feasibility of arching AMS and model data and to identify any limitations and issues with the process.

7.3 ARCHIVED DATA DESCRIPTION

The DMP developed in an AMS project should provide a description of the data collected during the project and details including the nature, scope and format of the data collected in the project. If a decision is made to use the MDIS for the AMS data clearinghouse, the data should include the linking attributes to MDIS and wherever possible the definitions and descriptions of the data elements should be according to MDIS definitions and descriptions of these elements. The descriptions should be provided in Metadata. Metadata is defined as the data that provides information about other data presented in a formal schema, allowing the users to determine what data and models are available and if and how they can be used for their projects, These descriptions should be provided in details in MDIS and the DMP to allow the use of the data and models in future projects. The DMP should be updated during the project tasks and at the end of the project, as necessary to keep the information current and reflect the actual collected and processed data and the modeling efforts, if modifications are made to the original plans.

Throughout the simulation projects, it is important to keep a detailed and updated record of the data collection, data processing, and the developed models to allow their eventual archiving in MDIS at the end of the project. The information provided for the collected and archived data can include but not limited to the following items:

a. The name and contact of the data creators: This can include the FDOT project manager, consultant project manager, the person(s) responsible for managing the data during the project, and the person responsible for archiving and maintaining the data after the project ends. The email contacts of the dataset creator(s) and maintainer should be provided.

b. Title of the data: The title can be the project title or an extension of it if needed

c. Location of the project: This is the name of the county and the modeled network with a location map indicating the location of the project.

d. Description: This is a brief description of the purpose and scope of the project and data in the form of an abstract that describes the purpose and scope of the project and related data and models.

e. Identifier: This is a unique object identifier (handle) to the dataset for the purpose of discovery, linking and citation.

f. Funding statement: The name of funding agency and contract numbers should be provided.

g. Data items: This is a list of all archived data, measure, modeling files, and document items that are archived (a comprehensive list of potential items are presented later in this section). It is realized that simulation projects will collect only a subset of the identified items in these sections.

h. Linking attributes: The linking attributes are specified to allow joining the AMS project datasets and other MDIS datasets, if MDIS is used for the AMS clearinghouse.

i. Data nature: This specifies the data nature for each of the data items specified in point “g” above such as continuous numerical data, categorical numerical data, image data, observational text sequences, video/audio, model input, model output, scripts and source code, etc.

j. Numerical data units: These are the units of the collected and archived data. There may be a difference in the units between the collected and archive data. For example, the count data may be collected in vehicle per minutes, but it is archived in vehicles per 15 minutes.

k. Utilized platform: Any platform and/or program used in producing, preparing, cleaning, and fusing, inputting, and outputting each of the data items. Examples of the platforms are SunGuide, RITIS, V2X data exchange platform, Signal Four, various Automated Traffic Signal Performance Measures (ATSPMs) platforms, various simulation modeling tools, and so on.

l. Creation method: The method used in creating the data such as moving car traffic studies, tube counts, manual turning counts, permanent and portable count stations, ITS point detectors, Bluetooth readers, crowdsource data from third party vendors, incident management data, connected vehicle data, and so on.

m. Temporal scope: This includes the date range of each collected data item and the period of time in the day that the data is collected for or a model is developed for.

n. Spatial scope: This includes the geographical coverage/locations of each collected data item and developed model in the archived data, Different data items may have different referencing schemes (mile post, latitude/longitude, etc.). Thus, the utilized referencing scheme will need to be specified for each item and correspond as much as possible to the referencing scheme in MDIS.

o. The temporal resolution of the archived data for each data items (e.g., 15-minute intervals)

p. Where applicable, information about problematic values, missing observations, and any weightings

q. Data file format: The file format (and version of the format if applicable), must be given. Examples of the data format are listed below:

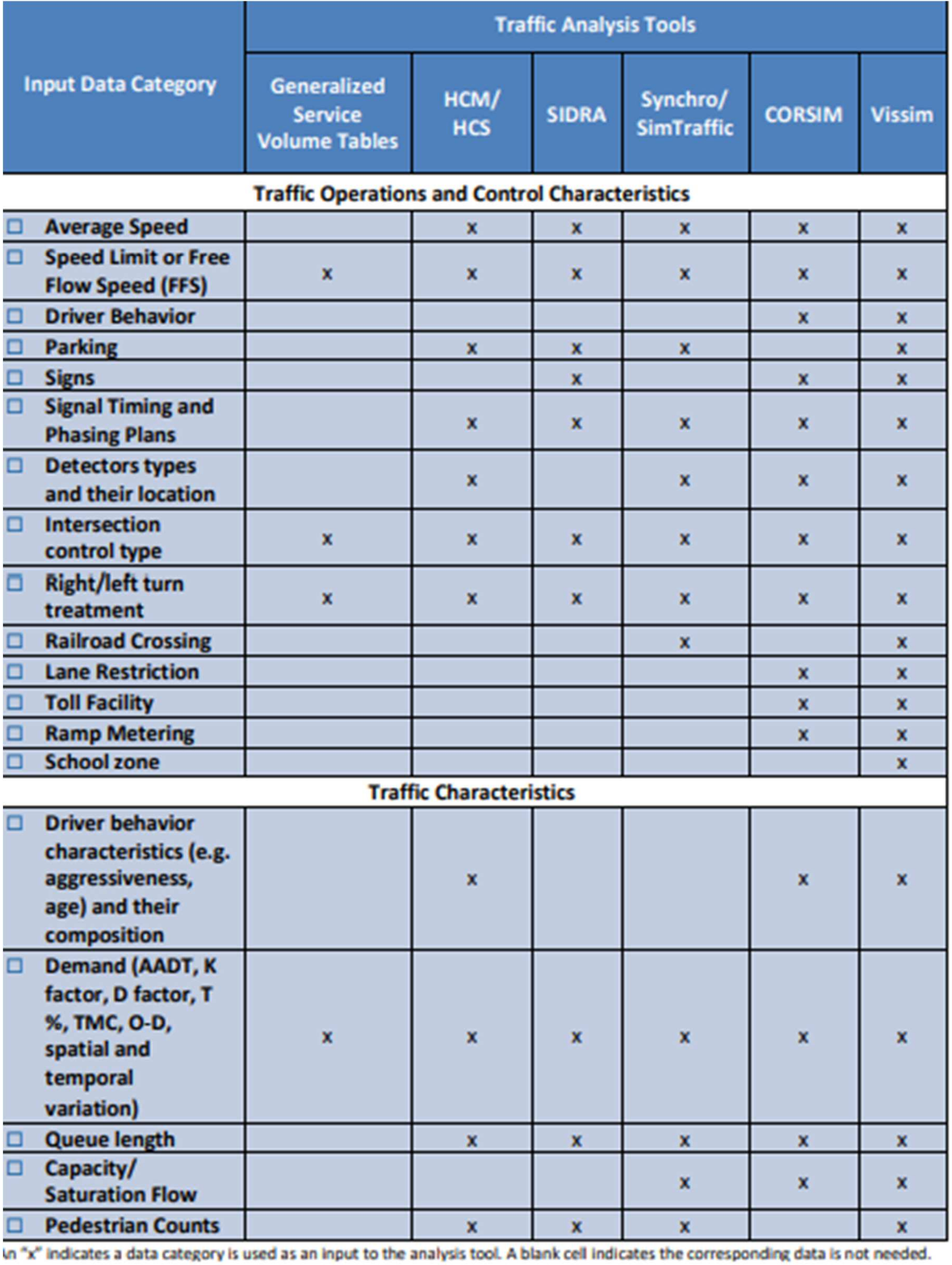
- MS Excel (.xls)
- MS Excel Macro (.xml)
- Comma Separated Values (.csv)
- Portable Document Format (.pdf)
- Rich Text Format (.rtf)
- Demand model specific inputs and output
- Simulation tool specific inputs and output
- Specific formats of other tool used to write modeling scripts and utilities (e.g., in Python, Matlab, C#, etc.)

- Joint Photographic Experts Group (.jpg)
- Video files (mpg, .avi, .mov, .wmv)
- Relational database tables

To the maximum degree possible, the data should be archived in a platform-independent and non-proprietary formats to ensure the best usability of the data in future efforts. The project team should provide the format for each data file and indicate if they are open or proprietary. Whenever feasible, excel spreadsheets should be used to store the data and metadata including the information outlined in Table 7-1 and Table 7-3. Project reports and other publications should be stored in Adobe PDF files. Any handwritten notes (field observations, sketches) and computer screen shots should be saved with other data as PDF files. It is recognized that the input and output files to simulation models are in binary priority format. If possible, the modeling files should be archived in both the binary format and in Rich Text Format (RTF).

Table 7-1 presents a list of data item that can be collected for AMS projects, as presented in the FDOT Traffic Analysis Handbook (FDOT, 2021b). The Transportation System Simulation Manual (TSSM), soon to be released by the Transportation Research Board (TRB) (TRB forthcoming), includes detailed requirements of the data needed for simulation modeling. These requirements are presented in Appendix A. It is realized that most of the simulation projects collects only a subset of the data in the Table 7-1 and Appendix A. In addition, there may be some data items that are needed for special cases that are missing in the table. Thus, the list of data items in Table 7-1 should be customized for each project. Table 7-3 summarizes the measures typically used for calibrating simulation models with the sources of the data, as presented in the Handbook (FDOT, 2021b).

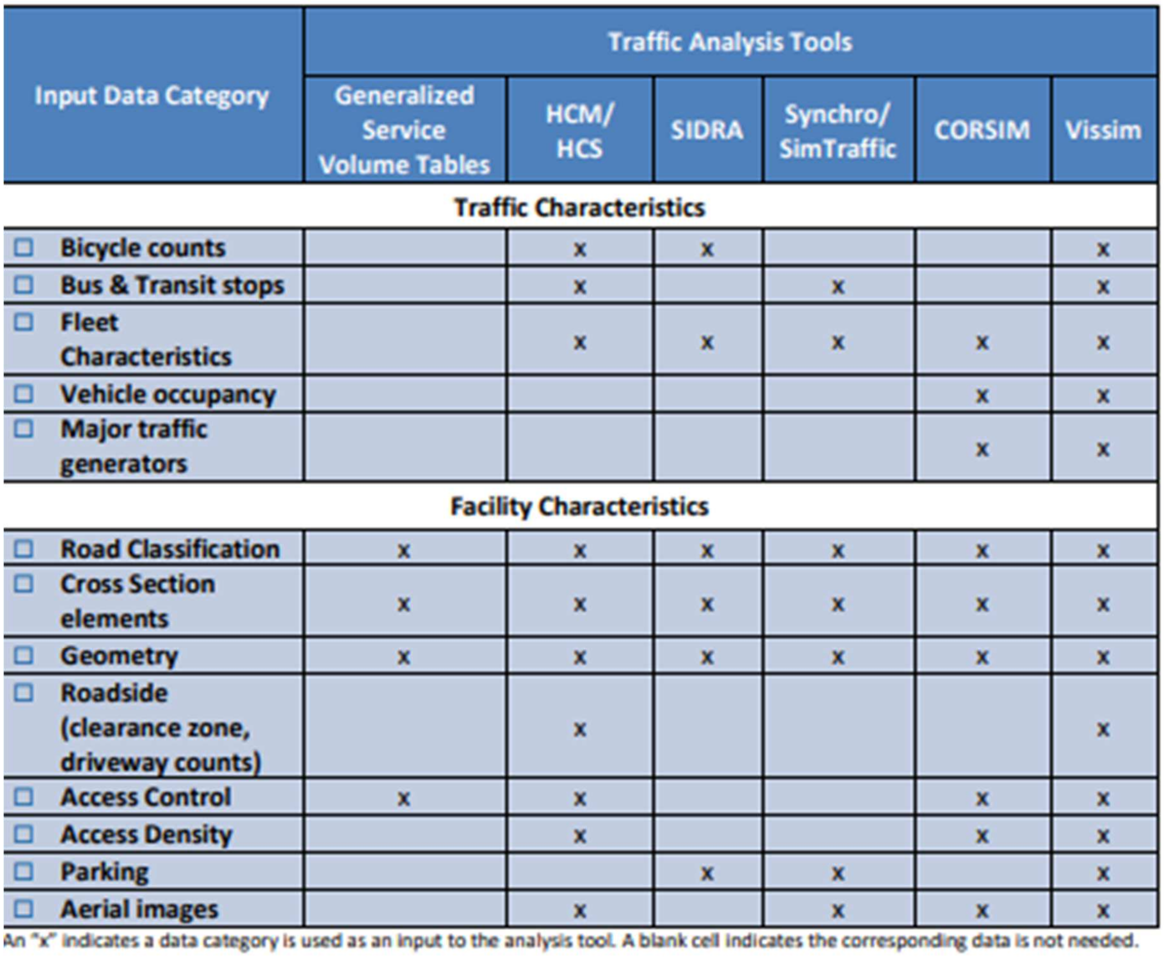
Table 7-1 Typical input data for different analysis types (Source: FDOT, 2021b)



Input Data Category	Traffic Analysis Tools					
	Generalized Service Volume Tables	HCM/ HCS	SIDRA	Synchro/ SimTraffic	CORSIM	Vissim
Traffic Operations and Control Characteristics						
☐ Average Speed		x	x	x	x	x
☐ Speed Limit or Free Flow Speed (FFS)	x	x	x	x	x	x
☐ Driver Behavior					x	x
☐ Parking		x	x	x		x
☐ Signs			x		x	x
☐ Signal Timing and Phasing Plans		x	x	x	x	x
☐ Detectors types and their location		x		x	x	x
☐ Intersection control type	x	x	x	x	x	x
☐ Right/left turn treatment	x	x	x	x	x	x
☐ Railroad Crossing				x		x
☐ Lane Restriction					x	x
☐ Toll Facility					x	x
☐ Ramp Metering					x	x
☐ School zone						x
Traffic Characteristics						
☐ Driver behavior characteristics (e.g. aggressiveness, age) and their composition		x			x	x
☐ Demand (AADT, K factor, D factor, T %, TMC, O-D, spatial and temporal variation)	x	x	x	x	x	x
☐ Queue length		x	x	x	x	x
☐ Capacity/ Saturation Flow				x	x	x
☐ Pedestrian Counts		x	x	x		x

n "x" indicates a data category is used as an input to the analysis tool. A blank cell indicates the corresponding data is not needed.

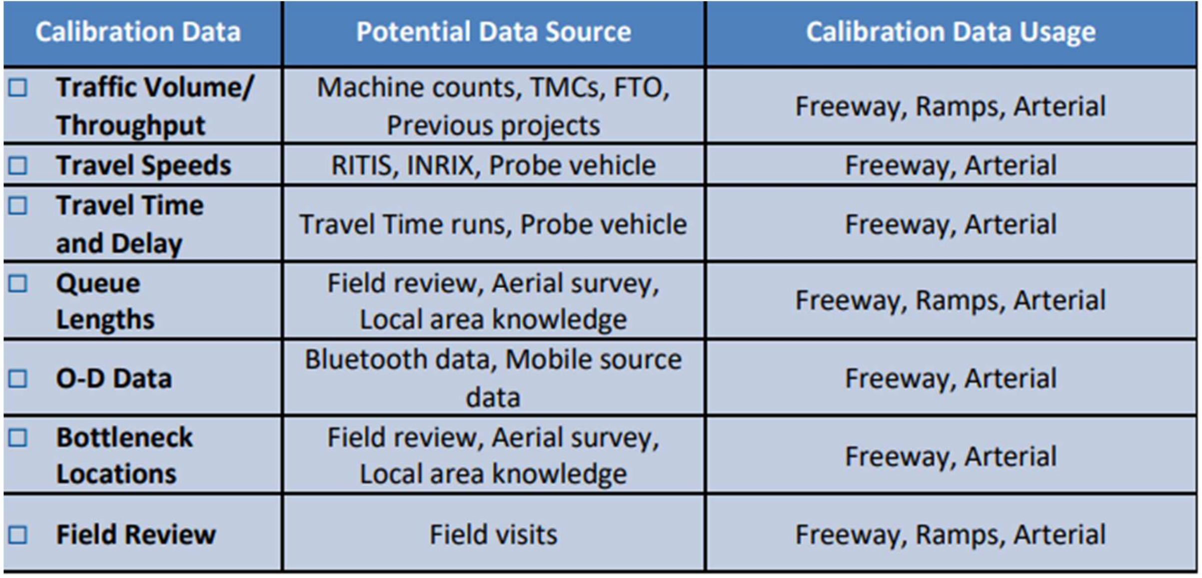
Table 7-2, continued



Input Data Category	Traffic Analysis Tools					
	Generalized Service Volume Tables	HCM/ HCS	SIDRA	Synchro/ SimTraffic	CORSIM	Vissim
Traffic Characteristics						
☐ Bicycle counts		x	x			x
☐ Bus & Transit stops		x		x		x
☐ Fleet Characteristics		x	x	x	x	x
☐ Vehicle occupancy					x	x
☐ Major traffic generators					x	x
Facility Characteristics						
☐ Road Classification	x	x	x	x	x	x
☐ Cross Section elements	x	x	x	x	x	x
☐ Geometry	x	x	x	x	x	x
☐ Roadside (clearance zone, driveway counts)		x				x
☐ Access Control	x	x			x	x
☐ Access Density		x			x	x
☐ Parking			x	x		x
☐ Aerial images		x		x	x	x

An "x" indicates a data category is used as an input to the analysis tool. A blank cell indicates the corresponding data is not needed.

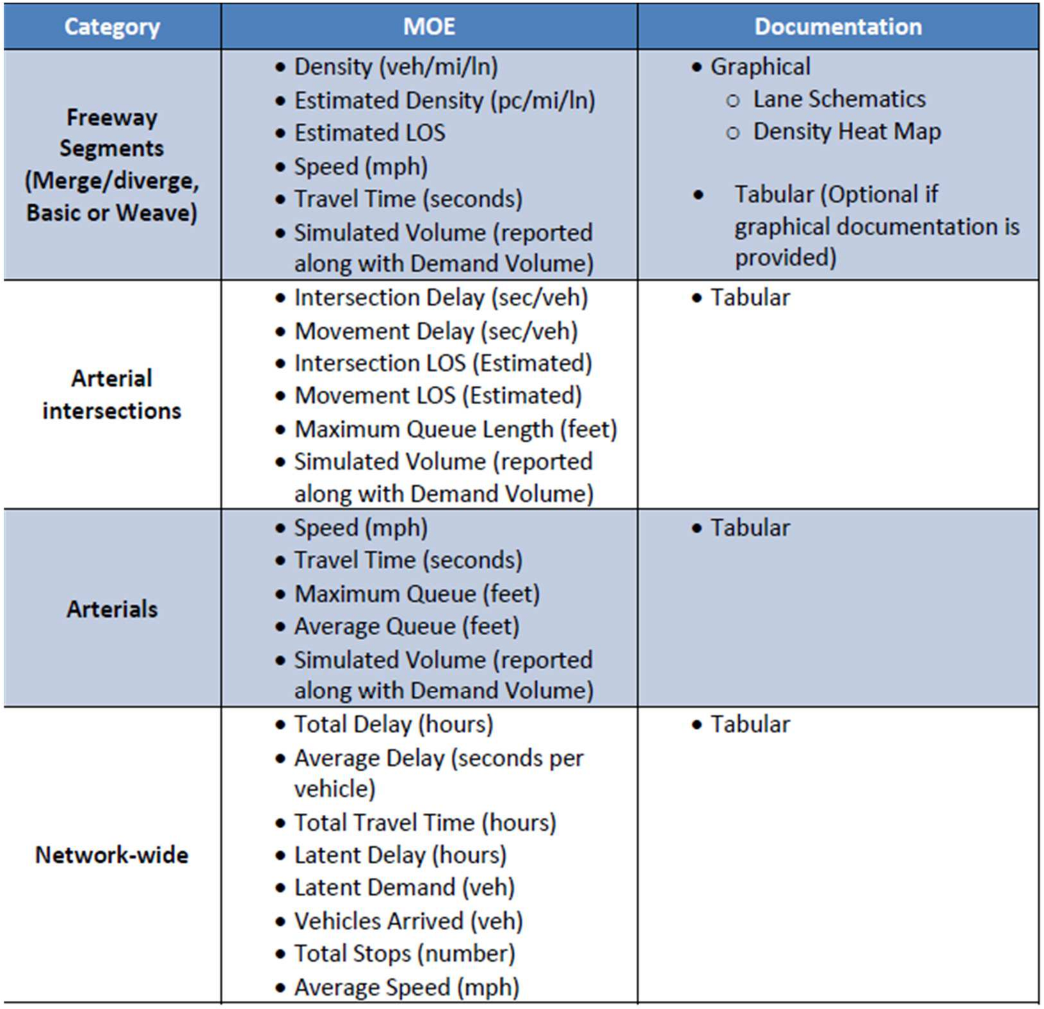
Table 7-3 Summary of calibration data with sources and usage (Source: FDOT, 2021b)



Calibration Data	Potential Data Source	Calibration Data Usage
☐ Traffic Volume/ Throughput	Machine counts, TMCs, FTO, Previous projects	Freeway, Ramps, Arterial
☐ Travel Speeds	RITIS, INRIX, Probe vehicle	Freeway, Arterial
☐ Travel Time and Delay	Travel Time runs, Probe vehicle	Freeway, Arterial
☐ Queue Lengths	Field review, Aerial survey, Local area knowledge	Freeway, Ramps, Arterial
☐ O-D Data	Bluetooth data, Mobile source data	Freeway, Arterial
☐ Bottleneck Locations	Field review, Aerial survey, Local area knowledge	Freeway, Arterial
☐ Field Review	Field visits	Freeway, Ramps, Arterial

In addition to the collected data, the main performance measures (such as travel times, delays, queue lengths, etc.) produced by the simulation models should be also archived and associated with segments, zones, or networks in other datasets in the clearinghouse (e.g., MDIS). Table 7-4 shows a list of typically utilized measures of effectiveness based on AMS results, as listed in the FDOT Traffic Analysis Handbook (FDOT, 2021b).

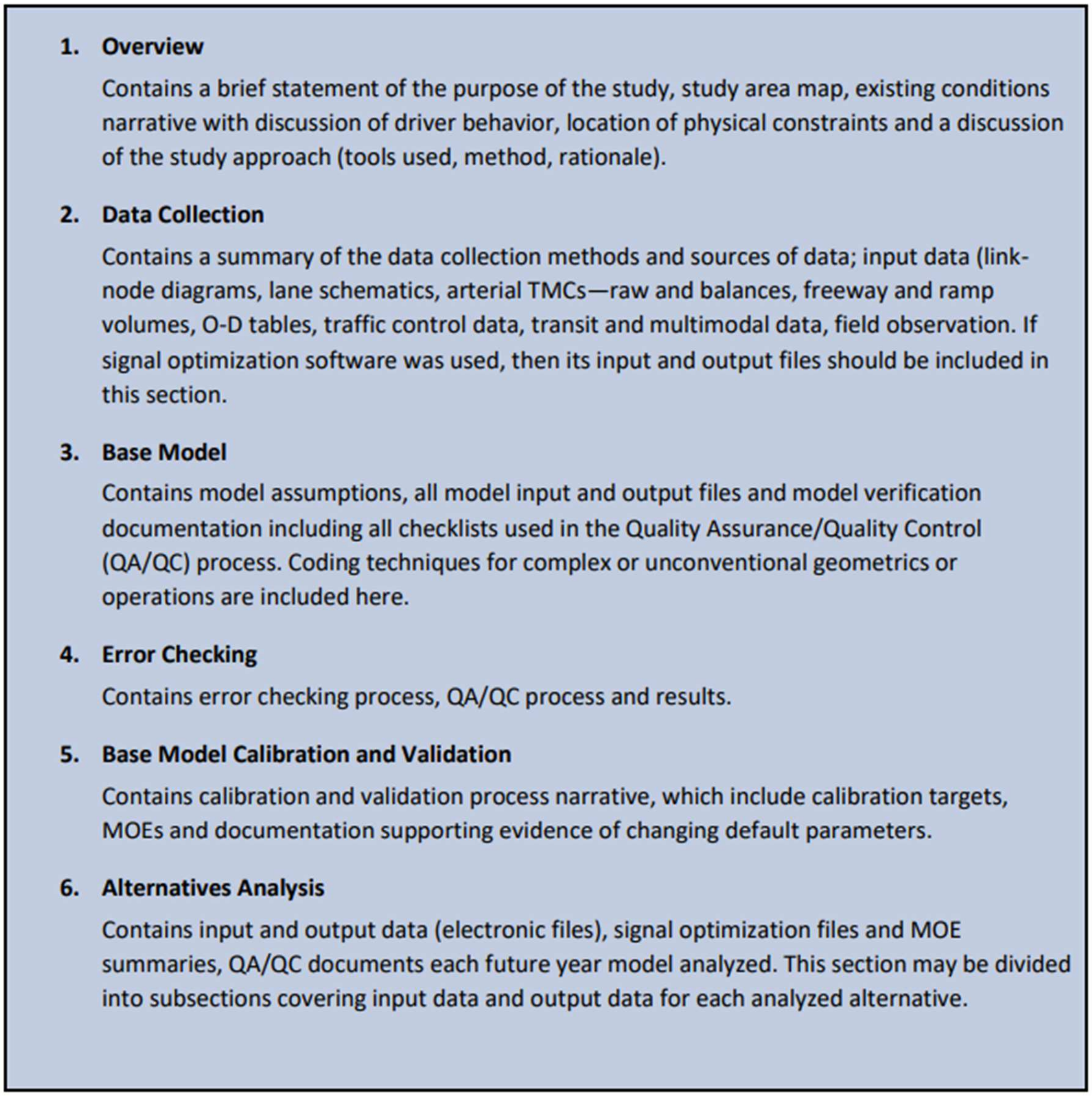
Table 7-4 Typically utilized measures of effectiveness based on AMS results (Source: FDOT, 2021b)



Category	MOE	Documentation
Freeway Segments (Merge/diverge, Basic or Weave)	• Density (veh/mi/ln) • Estimated Density (pc/mi/ln) • Estimated LOS • Speed (mph) • Travel Time (seconds) • Simulated Volume (reported along with Demand Volume)	• Graphical ○ Lane Schematics ○ Density Heat Map • Tabular (Optional if graphical documentation is provided)
Arterial intersections	• Intersection Delay (sec/veh) • Movement Delay (sec/veh) • Intersection LOS (Estimated) • Movement LOS (Estimated) • Maximum Queue Length (feet) • Simulated Volume (reported along with Demand Volume)	• Tabular
Arterials	• Speed (mph) • Travel Time (seconds) • Maximum Queue (feet) • Average Queue (feet) • Simulated Volume (reported along with Demand Volume)	• Tabular
Network-wide	• Total Delay (hours) • Average Delay (seconds per vehicle) • Total Travel Time (hours) • Latent Delay (hours) • Latent Demand (veh) • Vehicles Arrived (veh) • Total Stops (number) • Average Speed (mph)	• Tabular

The AMS clearinghouse should also archive the input/output files and other files produced by the simulation model as animation and vehicle trajectory files, any developed scripts and utilities, any input and output files of signal optimization software, if used, Archived model documentation should also in accordance with FDOT Traffic Analysis Handbook (FDOT, 2021b) guidance and TSSM guidance (TRB forthcoming) for traffic analysis documentation. The document should provide sufficient materials to review and verify the accuracy of the model and support additional analyses to be conducted either as part of future phases of the project or other future efforts that use the project simulation products. Table 7-5 shows an outline of the simulation project report, as recommended in the FDOT Traffic Analysis Handbook (FDOT, 2021b).

Table 7-5 Outline of the simulation project report, as recommended in the FDOT Traffic Analysis Handbook (FDOT, 2021b)



1. **Overview**

   Contains a brief statement of the purpose of the study, study area map, existing conditions narrative with discussion of driver behavior, location of physical constraints and a discussion of the study approach (tools used, method, rationale).

2. **Data Collection**

   Contains a summary of the data collection methods and sources of data; input data (link-node diagrams, lane schematics, arterial TMCs—raw and balances, freeway and ramp volumes, O-D tables, traffic control data, transit and multimodal data, field observation. If signal optimization software was used, then its input and output files should be included in this section.

3. **Base Model**

   Contains model assumptions, all model input and output files and model verification documentation including all checklists used in the Quality Assurance/Quality Control (QA/QC) process. Coding techniques for complex or unconventional geometrics or operations are included here.

4. **Error Checking**

   Contains error checking process, QA/QC process and results.

5. **Base Model Calibration and Validation**

   Contains calibration and validation process narrative, which include calibration targets, MOEs and documentation supporting evidence of changing default parameters.

6. **Alternatives Analysis**

   Contains input and output data (electronic files), signal optimization files and MOE summaries, QA/QC documents each future year model analyzed. This section may be divided into subsections covering input data and output data for each analyzed alternative.

The project documentation should include information about

- Existing conditions and study scope including the purpose of the study, study area map, existing conditions discussion and field observations, locations and nature of bottlenecks, modeling approach, modeling tools, temporal scope, spatial scope.

- Information about model development and associated parameters including method of inputting demands (turning percentages, static routes, dynamic assignment, etc.), link-node diagram if needed for the modeling software, lane schematics for the network, input and output files for all modeled peaks and scenarios, any script written for use for the tool of the API, simulation time step, modeled periods, modeled scenarios, methods of estimating measures based on calculated data, temporal resolution and justification for using these values, spatial extent of the network and justification, the analysis warm-up period, the analysis cool-down period, method used to estimate the O-D matrices if used as input to the model, modification of the default vehicle type and composition including the use of North American default, truck percentage, method used to model opposed movements at signalized and unsignalized intersections, module used to model signal control, method used to ensure assignment convergence, results from applying the method to ensure convergence, method used to verify dynamic routing decisions, and any other assumptions made during network coding.

- Information about the Verification, Calibration, and Validation (VCV) including description of the method to ensure that the model is verified and free of errors, model verification/error checking, unmet demands, filled VCV process checklists as presented in the FDOT traffic analysis handbook, calibration strategy and method, measures used in calibration, calibration targets (acceptance tolerances), results of the segments that meet/mot meet targets, parameters changed in the calibration the modifications made to the global and link-specific calibration model, validation method and results of the calibration model using an independent data set (data that was not used for calibration), justification for the changing of parameters from default parameters, any produced graphics and tables to confirm the quality of calibration and validation, and number of multiple simulation runs used in the calibration.

- Alternative analysis including the number of simulations runs, statement of how unmet demand is accounted for in the model, MOE reported in the output and used in the analysis, input file, text output files, binary output files, etc.

7.4 DATA ACCESS AND SHARING

The DMP of an AMS project should describe how the data files will be shared be shared and how others will access the data. One alternative that is being considered for this purpose in that all AMS project data and modeling items and the associated Metadata will be shared through MDIS. It is expected that additional information will become available regarding data sharing requirements as the design of the AMS clearinghouse and its possible incorporation in MDIS is complete. The DMP should state how the data can be accessed, indicating the software packages/tools required to access the data.

It is important in this introduction to highlight an issue with archiving AMS tools that can influence the effectiveness of the developed clearinghouse. The issue is that major new releases of the most existing tools are not backward compatible with the previous versions. This means a version created using an older version of a tool may not run with the new version of the model. It is recommended that the FDOT discusses with the tool vendors approaches to address this issue.

The DMP should also describe access and sharing restrictions that is applied to any of the collected or produced data items. This can include for example restrictions on sharing and/or using the data purchased from a third party vendors according to the purchase agreement. Another example is data that contain personally identifiable information, confidential business information, or classified information. The DMP should describe any efforts to mitigate such issues before archiving and/or accessing the data. This can include for example providing agreements or consent statements and steps to use the data. This can also include discussing additional steps to protect privacy and confidentiality such as de-identifying private and restricted data (anonymization measures) before depositing in the data archive. If such agreements and steps to resolve the issues cannot be identified, then the DMP should clearly identify the data access and sharing restrictions associated with the subject data items. If there are dates associates with these restrictions.

7.5 DISTRIBUTION AND REUSE OF DATA

The DMP should list the names and affiliation of those who have the rights to manage, administrate, and access the data during the project and after the project ended. The list of names should be approved by the FDOT project manager. If the data is stored and to be accessed through MDIS, the MDIS staff will have the administration and management rights after the AMS data and products are delivered to MDIS at the end of the project. The DMP should discuss any rights to be transferred to the data archive (e.g., MDIS). In addition, the DMP should specify any conditions for reuse, redistribution, and derivative products. A general FDOT policy may be set in this regard for use by the AMS teams in individual projects with the possibility of having exceptions as needed.

7.6 PLANS FOR ARCHIVING AND PRESERVATION

There are a number of options to archive the data generated from FDOT simulation projects. These options include

- Archive the data using a data repository maintained by the FDOT Central Office. The MDIS system described earlier has been identified as the candidate system for archiving simulation data, based on discussion with the FDOT Central Office.
- Archive the data using a data repository maintained by the FDOT District Office or MPO Office that sponsored the AMS project.

As stated earlier, MDIS is currently being considered for use as the platform to support the data use and exchange associated with FSUTMS Next Generation. It is recommended to also use this system for AMS data clearinghouse, considering the capability of the system and the opportunity for standardize various processes associated with data processing, management, governance, and sharing processes. Additional effort would be needed by the MDIS team to ensure that the use of the system for data capture, archiving, and provision will meet the needs of the AMS.

The archive system is expected to support metadata schema to facilitate the identification and use of the data. Accurate and consistent metadata should be assigned to the data. In addition, the archive system must support the creation and maintenance of persistent identifiers such as DOIs, handles, etc.

During the AMS project duration, the collected data and developed models, documents, and other products should be securely archived with information on how to prevent the loss or modification of data. This archiving process should consistently set a standard folder structure, folder names, file names, and versions.

7.7 COMMON NETWORK SPECIFICATIONS

As stated earlier, at least initially, the goal of the clearinghouse may be to just allow the users to download files and data associated with specific segments or zones, requiring just the use of standard metadata and linking attribute. However, a decision may be made for the use of input and output variables from AMS projects as attributes of data elements in the dataset such as links and subareas, standard specifications will be needed to define these variables such as those of MDIS, FSUTMS, the GMNS, or combinations. This section reviews the GMNS for potential use by FDOT, considering the advancement in MDIS development, AMS data clearinghouse, and multiresolution modeling. Even if this specification is not used by the FDOT, reviewing the GMNS effort products can provide useful information to modeling data exchange in Florida.

A common network specification will make it easier to share networks and will thus make it easier to share data models. The FSUTMS standards produced such a framework for demand forecasting modeling in Florida, As MDIS development, AMS data archiving, and multiresolution modeling practices advances; it will be useful to explore the use of such specifications that consider different type of AMS resolutions in data specifications. At the national level, there has been interest to develop such specifications for some time. A specification refers to as The GMNS has been developed by the Zephyr Foundation, with support from the Federal Highway Administration (FHWA) to facilitate the sharing of tools and data for modeling purposes (Berg et al., 2022; Zephyr Foundation, 2022). The first release of GMNS was January 2020 with a number of the updates since then. GMNS provides a common human and machine-readable format for sharing routable road network files, whose characteristics may vary by time of day and day of week. The motivation is to allow the use of time varying networks (e.g., varying lane configurations and tolls); and encouraging more consistent practices by state DOTs and MPOs for coding facilities, for easier automated processing of data, support multiresolution modeling projects, and support interchange of data between agencies and software packages. GMNS is a new effort, and it is expected that the specification will evolve and improve in the coming years. It is recommended that the FDOT and MDIS team investigate this specification for potential future use or for adopting some of the concepts to the existing and planned FDOT systems.

GMNS file specifications include nodes, links, lanes, locations, segments, movements, time-of-day specific files, and several auxiliary files. GMNS is extensible, in that the only required files are links and nodes, which are sufficient to support static network routing and several modes including Auto, Truck, Bus, Walk, and Bike. Extensions include data needed for dynamic networks such as:

- A segment file, with information that overrides the characteristics of a portion of a link.
- A lane file that allocates portions of the right-of-way. Lanes include travel lanes used by motor vehicles. They may also optionally include bike lanes, parking lanes, and shoulders.
- A segment lane file that specifies additional lanes, dropped lanes, or changes to lane properties on a segment of a link.
- A movement file that specifies how inbound and outbound lanes connect at an intersection

- Link, segment, lane and movement time-of-day (TOD) files, which allocates usage of network elements by time-of-day and day-of-week.
- Signal phase and timing files, for basic implementation of traffic signals.

Descriptions of each field of the data are provided on the GitHub site of the GMNS https://www.github.com/zephyr-data-specs/GMNS. Table 7-6 shows how the GMNS expresses the same concept in static and dynamic networks. Appendix B presents a list of the data elements in GMNS, with the first listed field is the primary key for each file, and required fields are shown in boldface.

Table 7-6 GMNS concepts in static and dynamic networks

Source: (Berg et al., 2022)

Concept	**Static (node-link) networks**	**Dynamic (detailed) networks**
Connections between links	Nodes connect the links, without regard to turning direction	Movements connect links, enabling some turns to be prohibited
Travel lanes	The lanes field on the link file provides the number of lanes available for motor vehicle travel	Lanes of all types (motor vehicle travel, bike, parking) are explicitly defined
Bicycle accommodation	bike_facility and allowed_uses fields on the link file	Explicit representation of bike lanes and other bicycle facilities
Pedestrian accommodation	ped_facility and allowed_uses fields on the link file	Pedestrian networks (sidewalks, crosswalks and other paths) are represented via undirected links and nodes
Link capacity	The product of lanes and capacity (per lane per hour) on the link file	Emerges from the explicit representation of lanes, movements and traffic controls
Traffic controls	Not explicitly represented	Represented via several files, with non-signalized controls (e.g., stop signs) on the movement file

7.8 SUMMARY AND RECOMMENDATIONS

This document providing recommendations for an AMS project clearinghouse for archiving and maintaining data, performance measures, analysis files, and documents. This study strongly recommends considering the use of the MDIS that is being developed by the FDOT as a candidate for use as the platform to support the data use and exchange associated with AMS projects. Additional effort would be needed by the MDIS team to ensure that the use of the system for data capture, archiving, and provision will meet the needs of the AMS.

It is recommended that the FDOT form a stakeholder group that involves public and private section simulation model users in Florida, the MDIS team, and the FDOT modeling and data leadership in early discussion to establish the AMS data clearinghouse with the potential use of MDIS of this project. It will also be very useful to identify at least one case study to demonstrate the feasibility of arching AMS and model data and to identify any limitations and issues with the process.

This document recommends that the project team of a traffic simulation project develops a Data Management Plan (DMP) according to the needs and requirements of the established framework.

The DMP will describe how the data and models of the analysis project will be generated, collected, managed, stored, protected, re-used, archived, and shared. The DMP and the clearinghouse will include metadata in a standard format, describe how the data will be managed and archived, outlines the access policies and methods including any restrictions on the access, re-use policies including any restrictions on the use of the data and model outputs.

If the goal of the clearinghouse is just allowing the users to download files and data associated with specific segments or zones, then the clearinghouse will require just the use of standard metadata and linking attribute. However, if a decision is made at the initial or later versions of the clearinghouse to use of input and output variables from AMS projects as attributes of data elements in the dataset such as links and subareas; standard specifications will be needed to define these variables such as those of MDIS, FSUTMS, the GMNS, or combinations. A common network specification will make it easier to share networks and will thus make it easier to share data and models. Even if this GMNS specification is not used by the FDOT, it is recommended that the FDOT review the GMNS for potential use considering the advancement in MDIS development, AMS data clearinghouse, and multiresolution modeling and the associated need for modeling data exchange in Florida.

One of the important issues that will impact the effectiveness of the clearinghouse recommended in this study is the issue that major new releases of the most existing tools are not backward compatible with the previous versions. This means a version created using an older version of a tool may not run with the new version of the model. It is recommended that the FDOT discusses with the tool vendors approaches to address this issue.

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APPENDIX A - SURVEY QUESTIONNAIRE

Microsimulation: Department Assessment and Guidance

FDOT Research Project BDV29 TWO 977-61

This research project will build on the existing state and national efforts to improve the Florida Department of Transportation microsimulation modeling practice through guidance and training. The proposed project will provide direction and updated guidance on using simulation to support various business processes of the FDOT and partner agencies considering the increased complexity and congestion of the transportation system and the adoption of advanced vehicle and infrastructure-based technologies and applications. The project activities will aim at bridging a common practice between the separate work groups in the Department that utilize and benefit from simulation modeling. Results from this research will lead to the development and utilization of more effective and accelerated understanding, review and delivery of Department guided simulation projects and will promote consistency of practice, enhanced training, and clearly defined expectations for microsimulation projects

1. **Name of agency**

   ____

2. **What types of analysis, modeling, and simulation (AMS) approaches are you using for facility, corridor, or network analysis? Check all that are available.**

   ☐ Macroscopic models (such as the tools that implement HCM facility procedures including FREEVAL, HCS, Synchro, etc.)

   ☐ Mesoscopic models

   ☐ Microscopic models

   ☐ Dynamic traffic assignment

   ☐ Multi-resolution simulation modeling (Using levels in sequence Macro→ Meso→ Micro)

   ☐ Hybrid simulation modeling (Using two different levels in the same run)

   ☐ Others. Please, specify ________________________

3. **What is your level of simulation experience?**

   ☐ Relatively inexperienced

   ☐ Moderate

   ☐ Relatively experienced

   ☐ Power user

   ☐ Others. Please, specify ________________________

4. **How often does your agency use microscopic simulation by size? (A Junction refers here to an intersection or an interchange)**

   Models with 1-10 junction per model - Number per year ________________________

   Models with 10-30 junction per model - Number per year ________________________

   Models with more than 30 junction per model - Number per year _________________

5. **What tools do use for simulation modeling? Please check all that apply.**

   ☐ CORSIM

   ☐ SimTraffic

   ☐ VISSIM

   ☐ TransModeler

   ☐ AIMSUN

☐ Dynameq

☐ Cube Avenue

☐ Others. Please, specify _________________________

Are you using any other tool in conjunction with the above tools to support the data management, development, calibration, and post –processing of the output?

Please, specify _________________________

Is there a process by which your agency decides on the use of the type of simulation modeling versus other analysis procedures? Please identify.

Please, specify _________________________

6. **Does your agency use formal guidelines or manuals for development and calibration of models?**

   Please, specify _________________________

   Please, comment on how the above guidance are used?

   Please, comment _________________________

7. **Please, list your experience in applying the guidance documents you listed above and what are the main deficiencies in the guidance?**

   Please, comment ________________________

8. **Do you think that there is a need for Florida general simulation guidance or tool specific guidance?**

   ☐ General simulation guidance

   ☐ Tool specific guidance

   ☐ Both

9. **Does your agency develop and calibrate simulation modeling based on the followings? Please check all that apply.**

   ☐ Turning movement and automatic tube counts

   ☐ Travel time test car studies

   ☐ Observations of queues or speeds

   ☐ Counts from ITS detectors

   ☐ Heavy vehicle composition by class

   ☐ Travel time data from Bluetooth/Wi-Fi readers

   ☐ Travel time data based on third-party vendor data (e.g., HERE, Inrix, NRDPMS)

☐ O-D data based on third party vendors

☐ O-D data obtained from demand models

☐ O-D data from demand models and refined using OD matrix estimation (ODME)

☐ Trajectory vehicle data that track vehicles at a fraction of second intervals.

☐ Other (please specify) _________________________

☐ Please, comment on any data issue and needs _________________________

10. Please, comment on issues and needs in the calibration of the simulation models

Please, comment _________________________

11. What performance measures are currently used or needed based on the output of simulation models?

☐ Queue data

☐ Travel time measurements/ Delays

☐ Number of stops

☐ Reliability

☐ Emission

☐ Safety surrogate measures

☐ Level of service

☐ Others (please specify) _________________________

11. How are simulation models generated (in-house or consultants)

☐ Both development and review in-house

☐ Development by consultants – review in house

☐ Both development and review by consultants

12. Does your agency and consultant have sufficient technical staff to develop and review models to meet simulation needs?

☐ Yes, there is sufficient staff to meet development and review needs

☐ There is sufficient staff to meet development but not review needs

☐ There is sufficient staff to meet review but not development needs

☐ No, there is no sufficient staff to meet development and review needs

Please, comment _________________________

13. Does your agency have adequate budget to meet simulation needs?

☐ Yes

☐ No

Please, comment _________________________

Please, comment on how you estimate the number of hours required in the analysis _________________________

14. Please, identify any issues regarding the utilization of demand forecasting model outputs as inputs to simulation modeling?

Please, comment _________________________

15. What is the procedure that you use and your experience in modeling future year networks and demand inputs to simulation model?

Please, comment _________________________

16. What is your interest and need in applying simulation models for emerging connected, automated, shared, and electric vehicle applications?

Please, comment _________________________

17. Do you archive and maintain the simulation models after the end of the project?

Please, comment _________________________

18. What are your training needs?

Please, comment _________________________

19. What are additional issues, barriers, needs, and concerns facing your agencies in using simulation?

Please, comment _________________________

20. Respondent Information

Name ....

Title ....

Affiliation ....

Phone ....

E-mail ....

Thank you very much for your input. It is greatly appreciated!

APPENDIX B - SIMULATION DATA REQUIREMENTS AS PRESENTED IN THE TRANSPORTATION SYSTEM SIMULATION MANUAL (TSSM) (TRB FORTHCOMING)

Table B-1 Geometric Data Requirements for Analysis Types: signalized/unsignalized intersections, roundabouts, non-traditional intersections/interchanges, ped/bike lanes

GEOMETRIC PARAMETERS	ANALYSIS TYPES			
	Signalized intersections, unsignalized intersections, and arterials	Roundabouts	Non-traditional intersections/ interchanges (SPUI, CFI, DLT)	Pedestrians and bicycles (on- and off-street)
Aerial imagery	✓	✓	✓	✓
Number of lanes	✓	✓	✓	✓
Location of preemption devices	✓	-	✓	-
Approach grade	✓	✓	✓	-
Lane widths	✓	✓	✓	✓
Storage bay lengths	✓	✓	✓	-
Taper lengths	✓	-	✓	-
Intersection approach widths	✓	✓	✓	✓
Shoulder widths	✓	-	✓	✓
Lane designations	✓	✓	✓	-
Presence of pedestrians or bike lanes	✓	✓	✓	✓
Length of passing lane(s), if present	-	-	-	-
Length of no-passing zone(s)	-	-	-	-

Source: FHWA, adapted from Virginia Department of Transportation (2015).
SPUI = single-point urban interchange. CFI = continuous flow intersection. DLT = displaced left-turn intersection.
- = data not required.
Source: FHWA.

Table B-2 Geometric Data Requirements for Analysis Types: signalized/unsignalized intersections, roundabouts, non-traditional intersections/interchanges, ped/bike lanes. (continuation)

GEOMETRIC PARAMETERS	ANALYSIS TYPES			
	Signalized intersections, unsignalized intersections, and arterials	Roundabouts	Non-traditional intersections/ interchanges (SPUI, CFI, DLT)	Pedestrians and bicycles (on- and off-street)
Roundabout approach widths	-	✓	-	-
Ped/bike crossing distances	✓	✓	✓	✓
Roadside shoulder slope	-	-	-	✓
Interchange configuration	-	-	✓	-
Ramp length and radii	-	-	✓	-
Acceleration/deceleration lane lengths	-	-	✓	-
Distances to adjacent interchanges	-	✓	✓	-
Distance to upstream warning signs		-	✓	-
Driveway spacing	✓	-	✓	-
Median data	✓	✓	✓	✓
Distance to constricting Infrastructure	✓	✓	✓	✓
Payment choices	-	-	-	-
Time of day restrictions	✓	-	-	-

Source: FHWA, adapted from Virginia Department of Transportation (2015).

SPUI = single-point urban interchange. CFI = continuous flow intersection. DLT = displaced left-turn intersection.

- = data not required.

Source: FHWA.

Table B-3 Traffic Count Data Requirements for Analysis Types: signalized/unsignalized intersections, roundabouts, non-traditional intersections/interchanges, ped/bike lanes

TRAFFIC DATA PARAMETERS	**ANALYSIS TYPES**				
	Signalized intersections, unsignalized intersections, and arterials	Signalized intersection preemption and transit priority	Roundabouts	Non-traditional intersections/ interchanges (SPUI, CFI, DLT)	Pedestrians and bicycles (on- and off-Street)
Peak hour turning movement counts	✓	✓	✓	✓	✓
Automated traffic recorder counts	✓	✓	-	✓	✓
Annual average daily traffic (AADT)	-	-	-	-	-
Parking maneuvers	✓	✓	✓	✓	-
Transit service data	✓	✓	✓	✓	-
Vehicle classification data	✓	✓	✓	✓	-
Speed data	✓	✓	✓	✓	-
Toll plaza and gate lane data	-	-	-	-	-

Source: FHWA, adapted from Virginia Department of Transportation (2015).

SPUI = single-point urban interchange. CFI = continuous flow intersection. DLT = displaced left-turn intersection.

- = data not required.

Source: FHWA.

Table B-4 Calibration Data Requirements for Analysis Types: signalized/unsignalized intersections, roundabouts, non-traditional intersections/interchanges, ped/bike lanes

CALIBRATION DATA PARAMETERS	ANALYSIS TYPES				
	Signalized intersections, unsignalized intersections, and arterials	Signalized intersection preemption and transit priority	Roundabouts	Non-traditional intersections/ interchanges (SPUI, CFI, DLT)	Pedestrians and bicycles (on- and off-Street)
Peak hour/period traffic demand	✓	✓	✓	✓	-
Pedestrian and bicycle travel speeds	-	-	-	-	✓
Mainline speed data	✓	✓	✓	✓	-
Ramp speed data	-	-	-	✓	-
Toll lane and gate processing time by payment choice	-	-	-	-	-
Travel times	✓	✓	-	✓	-
Queuing data	✓	✓	✓	✓	-
Existing crash data	-	-	-	-	-

Source: FHWA, adapted from Virginia Department of Transportation (2015).

SPUI = single-point urban interchange. CFI = continuous flow intersection. DLT = displaced left-turn intersection.

- = data not required.

Table B-5 Geometric Data Requirements for Analysis Types: freeways/interchanges, two-lane highways, multilane highways

GEOMETRIC PARAMETERS	ANALYSIS TYPES		
	Freeways/ interchanges (merge, diverge, weave, collector-distributor)	Two-lane highways	Multilane highways
Aerial imagery	✓	✓	✓
Number of lanes	✓	-	✓
Location of preemption devices	-	-	-
Approach grade	✓	✓	✓
Lane widths	✓	✓	✓
Storage bay lengths	-	-	✓
Taper lengths	-	-	✓
Intersection approach widths	-	-	-
Shoulder widths	✓	✓	✓
Lane designations	✓	-	✓
Presence of pedestrians or bike lanes	-	✓	✓
Length of passing lane(s), if present	-	✓	-
Length of no passing zone(s)	-	✓	-
Roundabout approach widths	-	-	-
Ped/Bike crossing distances	-	-	-
Roadside shoulder slope	-	-	-
Interchange configuration	✓	-	-
Ramp length and radii	✓	-	-
Acceleration/deceleration lane lengths	✓	-	-
Distances to adjacent interchanges	✓	-	-
Distance to upstream warning signs	✓	-	-
Driveway spacing	-	-	✓
Median data	-	-	✓
Distance to constricting infrastructure	✓	✓	✓
Payment choices	-	-	-
Time of day restrictions	-	-	-

Source: FHWA, adapted from Virginia Department of Transportation (2015).
- = data not required.

Table B-6 Traffic Count Data Requirements for Analysis Types: freeways/interchanges, two-lane highways, multilane highways.

TRAFFIC DATA PARAMETERS	ANALYSIS TYPES		
	Freeways/ interchanges (merge, diverge, weave, collector-distributor)	Two-lane highways	Multilane highways
Peak hour turning movement counts	-	-	✓
Automated traffic recorder counts	✓	✓	-
Annual average daily traffic (AADT)	-	-	-
Parking maneuvers	-	-	✓
Transit service data	-	-	✓
Vehicle classification data	✓	✓	✓
Speed data	✓	✓	✓
Toll plaza and gate lane data	-	-	-

Source: FHWA, adapted from Virginia Department of Transportation (2015).
- = data not required.

Table B-7 Calibration Data Requirements for Analysis Types: freeways/interchanges, two-lane highways, multilane highways.

CALIBRATION DATA PARAMETERS	ANALYSIS TYPES		
	Freeways/ interchanges (merge, diverge, weave, collector-distributor)	Two-lane highways	Multilane highways
Peak hour/period traffic demand	✓	✓	✓
Pedestrian and bicycle travel speeds	-	-	-
Mainline speed data	✓	✓	✓
Ramp speed data	✓	-	-
Toll lane and gate processing time by payment choice	-	-	-
Travel times	✓	✓	✓
Queuing data	✓	-	✓
Existing crash data	-	-	-

Source: FHWA, adapted from Virginia Department of Transportation (2015).
- = data not required.

Table B-8 Geometric Data Requirements for Analysis Types: work zone traffic, toll plazas, gated lanes, managed lanes, ramp metering, safety analyses.

GEOMETRIC PARAMETERS	ANALYSIS TYPES			
	Work zone traffic (freeway or arterial)	Toll plazas and gates	Managed lanes or ramp metering	Safety analyses
Aerial imagery	✓	✓	✓	✓
Number of lanes	✓	✓	✓	✓
Location of preemption devices	✓	-	-	-
Approach grade	✓	-	-	✓
Lane widths	✓	✓	✓	✓
Storage bay lengths	✓	-	-	-
Taper lengths	✓	-	-	-
Intersection approach widths	✓	-	-	-
Shoulder widths	✓	-	-	✓
Lane designations	✓	✓	✓	✓
Presence of pedestrians or bike lanes	✓	-	-	✓
Length of passing lane(s), if present	✓	-	-	-
Length of no passing zone(s)	✓	-	-	-
Roundabout approach widths	✓	-	-	-
Ped/bike crossing distances	✓	-	-	✓
Roadside shoulder slope	✓	-	-	✓
Interchange configuration	✓	-	-	✓
Ramp length and radii	✓	✓	-	✓
Acceleration/deceleration lane lengths	✓	✓	-	✓
Distances to adjacent interchanges	✓	-	-	✓
Distance to upstream warning signs	✓	✓	✓	-
Driveway spacing	✓	-	-	✓
Median data	✓	-	-	✓
Distance to constricting infrastructure	✓	✓	✓	✓
Payment choices	✓	✓	-	-
Time of day restrictions	✓	-	✓	-

Source: FHWA, adapted from Virginia Department of Transportation (2015).

- = data not required.

Table B-9 Calibration Data Requirements for Analysis Types: work zone traffic, toll plazas, gated lanes, managed lanes, ramp metering, safety analyses.

CALIBRATION DATA PARAMETERS	ANALYSIS TYPES			
	Work zone traffic (freeway or arterial)	Toll plazas and gates	Managed lanes or ramp metering	Safety analyses
Peak hour/period traffic demand	✓	✓	✓	-
Pedestrian and bicycle travel speeds	-	-	-	-
Mainline speed data	✓	✓	-	-
Ramp speed data	✓	-	-	-
Toll lane and gate processing time by payment choice	✓	✓	-	-
Travel times	✓	✓	✓	-
Queuing data	✓	✓	-	-
Existing crash data	-	-	-	✓

Source: FHWA, adapted from Virginia Department of Transportation (2015).
- = data not required.

APPENDIX C - GENERAL MODELING NETWORK SPECIFICATION (GMNS) DATA ELEMENTS

(Source: Berg et al. 2022)

Figure C-1 shows the relationships among links, lanes, segments, and their time-of-day files in the GMNS. Table C-1 lists the GMNS elements (Berg et al., 2022). The first listed field is the primary key for each file, and required fields are shown in boldface. Detailed descriptions of each field are provided on the GitHub site at https://www.github.com/zephyr-data-specs/GMNS.

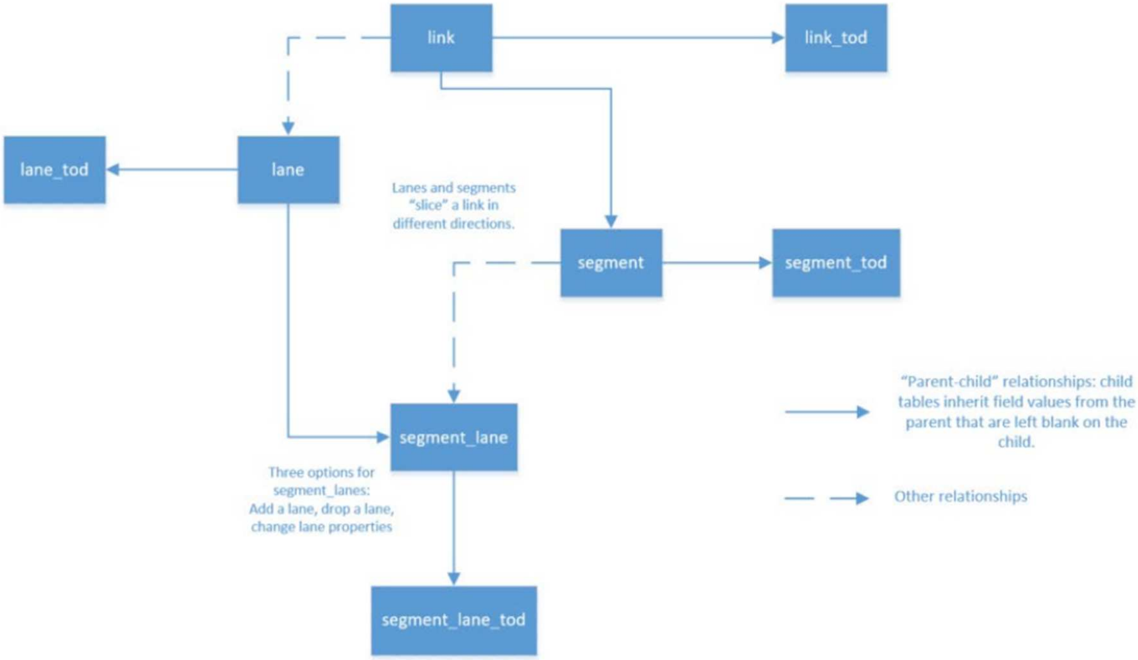

Figure C-1 Relationships between the GMNS Files

Table C-1 GMNS Elements

File	Description	Fields
node	a point that connects links	**node_id**, name, **x_coord, y_coord**, z_coord, node_type, ctrl_type, zone_id, parent_node_id
link	a directed or undirected line object in a network, defined by the nodes it travels from and to	**link_id**, name, **from_node_id, to_node_id, directed**, geometry_id, geometry, parent_link_id, dir_flag, length, grade, facility_type, capacity, free_speed, lanes, bike_facility, ped_facility, parking, allowed_uses, toll, jurisdiction, row_width
link_tod	day-of-week and time-of-day restrictions on a link	**link_tod_id, link_id,** time_day, timeday_id, capacity, free_speed, lanes, bike_facility, ped_facility, parking, allowed_uses, toll
geometry	contains shapepoints for a line object	**geometry_id,** geometry
lane	a portion of the physical right-of-way that might be used for travel	**lane_id, link_id, lane_num,** allowed_uses, r_barrier, l_barrier, width
lane_tod	day-of-week and time-of-day restrictions on a lane	**lane_tod_id, lane_id,** time_day, timeday_id, lane_num, allowed_uses, r_barrier, l_barrier, width
location	point that is associated with a specific location along a link, using a linear reference (lr)	**loc_id, link_id, ref_node_id, lr**, x_coord, y_coord, z_coord, loc_type, zone_id, gtfs_stop_id
movement	connection between inbound and outbound links or lanes at an intersection	**mvmt_id, node_id**, name, **ib_link_id**, start_ib_lane, end_ib_lane, **ob_link_id**, start_ob_lane, end_ob_lane, **type**, penalty, capacity, **ctrl_type**, mvmt_code,