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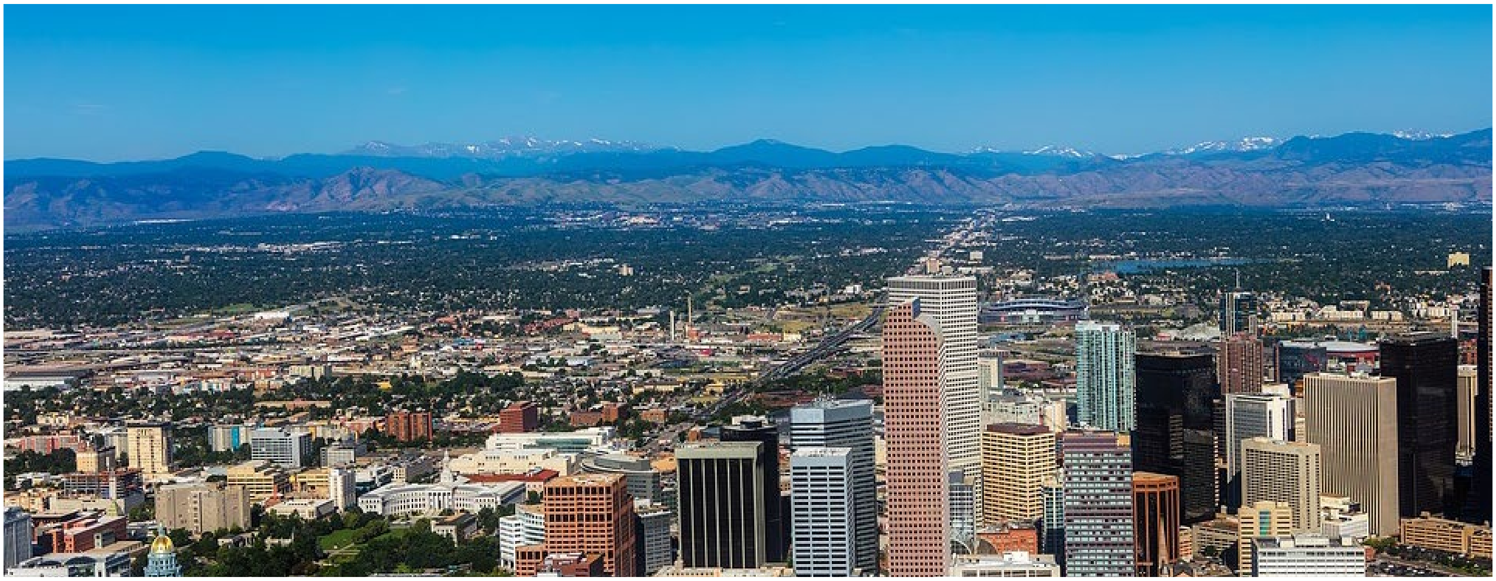
CDOT Dynamic Traffic Assignment (DTA) Implementation Plan



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16. Abstract

This report presents a vision and an implementation plan for region-wide dynamic traffic assignment (DTA) in Colorado. With the proper approach and methods, DTA can be a powerful and cost-effective decision support tool for CDOT's and MPOs' transportation planning and engineering responsibilities and activities. In the report, simulation-based DTA models are described, and their key features are explained and placed in the context of current traffic microsimulation and travel demand modeling practices.

DTA makes it possible to address numerous traffic management and operations strategies, to improve project evaluation, and, with suitable implementation and application, realize benefits in the form of reduced traffic delay, improved safety, lower greenhouse gas emissions, and greater toll revenues from dynamically-priced facilities. DTA will also reduce costs and improve the quality and consistency of future simulation studies.

The report outlines a recommended technical approach to DTA employing regional mesoscopic simulation with capabilities for hybrid mesoscopic-microscopic simulation for increased detail and accuracy when needed. The report provides an implementation plan for realizing the technical approach and capturing the benefits of DTA in metropolitan areas big and small across Colorado. The implementation plan identifies steps, methods, best practices, and recommendations for successful DTA development, calibration, and application.

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Executive Summary

This report presents a recommended approach and implementation plan for development and use of Dynamic Traffic Assignment (DTA) models by CDOT and Colorado MPOs. DTA models in their most recent incarnation combine traffic simulation with a mechanism for accommodating travelers' route choices as they adapt to varying traffic conditions and various new options such as express lanes with time-varying tolls.

DTA models are much more realistic than the traffic assignment models found in MPO and statewide models as they treat the temporal nature of traffic directly and not simply in terms of aggregates over hourly or multiple-hour peak periods. DTA models also treat vehicle behavior and congestion in a more realistic fashion, making them suitable for operational analysis of system performance and traffic management strategies.

There are various types of DTA models that differ in the form of simulation upon which they rely. These simulation models may be mesoscopic or microscopic. Mesoscopic models are based on speed-density relationships while microscopic models move individual vehicles based upon physical factors of acceleration, deceleration, car-following, and lane changing. Microscopic simulation also treats traffic signals more realistically. For these reasons, DTA using microsimulation is to be preferred in our opinion. However, microsimulation is computationally demanding and may not be feasible for the widest areas. For this reason, we have recommended that a hybrid approach be adopted in which part of the transportation network is simulated microscopically and the remainder is simulated mesoscopically where and when necessary.

To be valid, the input values assumed in simulation models must be consistent with their outputs. In particular, the input network travel times by road segment assumed in the routing of vehicles must be consistent with the network travel times experienced in the model. From a decisionmaker's perspective, DTA models impose this consistency and thus make simulation a much more reliable tool than it would otherwise be.

Applications of DTA models target a wide range of contemporary transportation planning and management issues and should be instrumental in achieving key transportation benefits including those listed below.

- Delay Reduction
- Improved Travel Reliability
- Reduced Accident Rates
- Lower Greenhouse Gas Emissions
- Increased Express Lane Revenues
- Improved Project Selection
- Greater readiness for new technologies such as Connected & Automated Vehicles

These and other benefits are addressed and explained in the report.

As part of the implementation plan development, we reviewed prior work on DTA nationwide and in Colorado. Some DTA models have been developed in Colorado and applied in toll and revenue and in other studies that relied upon traffic simulation. Our review suggested that the state of the practice would be improved if there was a regional DTA resource for the Denver region and that there would be substantial cost savings as well.

We also interviewed stakeholders to understand their desired goals and objectives where traffic modeling and analysis are concerned. Stakeholders expressed clear interest in detailed modeling of baseline conditions and new projects and strategies. They also stressed the need for policy relevance and potential integration with existing travel demand models. Our recommended approach is responsive to these inputs.

The vision that we propose for CDOT is to use DTA as a "digital twin" or realistic laboratory with which to evaluate projects, operational improvements, and management strategies including dynamic tolling and use of future new technologies. At the same time, we believe that wide-area DTA resources will upgrade traffic simulation studies, reduce their costs, and remove inconsistencies and redundancies in their application.

Development of a baseline model is the key element in the implementation plan. A baseline model would encompass the Denver region and possibly additional heavily utilized roadways.

In the report, we discuss the data requirements for building successful DTA models in Colorado. In addition to existing information systems, there are new sources of data from cell phone apps and connected vehicles that can reduce the effort and increase the realism of future DTA models.

DTA models require substantial calibration and validation. These technical efforts require specialized expertise and sufficient time to complete the work. We recommend that implementation of a DTA be performed over an 18 month to 2-year period for that reason.

The implementation plan discusses a recommended management approach, barriers to development and deployment of a regionwide DTA, and the necessary maintenance, training, and technical support activities for a successful implementation. Overall, the case for DTA, and more broadly for modeling projects before they are finalized and implemented, is compelling and will return benefits greatly in excess of analysis costs.

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1.0 INTRODUCTION

This document describes a plan for implementation of a valuable transportation planning resource for Colorado Department of Transportation (CDOT) and Metropolitan Planning Organizations (MPOs) in the state. That resource is the traffic modeling technique known to transportation planners and traffic modelers as dynamic traffic assignment (DTA). DTA marries two modeling techniques that are long and well established in the state of the practice in Colorado: traffic assignment, traditionally used by MPOs to forecast traffic volumes on the regional road network, and traffic simulation, a favored tool of traffic engineers seeking to predict the operational impacts of proposed projects within a relatively confined area of study.

DTA application has been on the rise in Colorado in recent years and has been trending toward increasingly wider study areas, even those as large as an entire metropolitan area, in other parts of the US. This trend toward wider-area application has been driven by the need to examine the effects of a project on the routes drivers take. Projects that add capacity and/or introduce tolls can have profound impacts on how travelers use the road network that cannot be studied with either traditional traffic assignment or traffic simulation tools, for reasons that will be described in this document.

Simultaneously, the trend toward wide-area DTA modeling has been enabled both by dramatic increases in computing power and by broadening recognition of the cost savings that can be achieved when supporting databases of traffic data and inventory are properly leveraged in DTA model development. Those databases are a resource well known to transportation professionals at CDOT, which routinely purchases or maintains a broad array of traffic inventory and geographic information, including historical traffic count and speed data.

This document is intended to explain the usefulness and characteristics of a DTA as a resource for regional and statewide planning and to recommend a technical approach. We describe the principal benefits to be expected from a DTA program, present a vision for statewide application of DTA models, and then enumerate and discuss the key elements of an implementation plan tailored to CDOT needs.

1.1 WHAT IS DTA?

The aim of effective DTA models is to incorporate queuing and spillback effects between adjacent and parallel facilities in ways that traditional assignments do not and to provide a sound basis for project evaluation, design, and transportation facility management when those effects are present. There are, however, many types of DTA, and only some will fulfill that requirement. Before discussing the various types of DTA, some background on simulation models is useful.

For the most detailed analysis of traffic flow and traffic management schemes, microsimulation models are used. In microsimulation, the movement of each vehicle is simulated at sub-second time intervals, and vehicles accelerate and decelerate, follow other vehicles, change lanes, respond to traffic signals, and perform a variety of other driving tasks. These driving tasks, when modeled correctly, are subject to the laws of physics and the constraints of vehicle dynamics, which are influenced by roadway geometry and other design characteristics.

Mesoscopic simulation models, which are an alternative to microsimulation and are common among DTA platforms, use simpler empirical relationships between traffic density and speed to model traffic flow but sacrifice much of the detail available in a microsimulation. To reduce model running times, some of the more critical details that are necessarily sacrificed when using mesoscopic simulation are those relating to traffic signal operation and vehicle dynamics.

A traffic simulation, whether microscopic or mesoscopic, is a probabilistic model. Typically, multiple replications are required to assess a scenario with any degree of reliability. Unlike travel demand models, simulation models can provide a range of possible impact estimates.

For these reasons – the high level of detail in microsimulation models and the requirement of multiple replications – microsimulation has historically largely been a tool of traffic engineers for the study of small areas. In early practice, simulation models were used only for small problems involving a few street segments or only a few miles of a highway. Also, the simulations were based on turning movement volumes input at each intersection in the network. Routes taken by simulated vehicles were thus predetermined either by field measurements or analyst judgment rather than an outcome of a route choice model sensitive to congestion patterns that may vary between project alternatives. As a result, those models could be considered animations of traffic scenarios rather than models of traffic flow.

Many transportation projects and management schemes will cause some drivers to change their routes in response to changing traffic conditions. Changes in routes will also be commonly observed when there are incidents or work zones on the road network. In modern simulation modeling practice, drivers choose routes based upon estimates of the travel times and other characteristics, such as toll prices of the best routes available at their departure times.

Whereas in the past, there was little information available to modelers about the travel times on network segments by time of day and even less information about the routes that vehicles choose, this is no longer the case. Navigation systems provide robust routing recommendations, and various electronic devices and mobile app developers provide a wealth of data on operating conditions and traveler choices. These recommendations and data can potentially be mined and leveraged to develop detailed and accurate simulation models.

1.2 TYPES OF DTA MODELS

There are various types of DTA models, and it is important to distinguish among them. Not surprisingly, they vary in network representation, in the way that vehicles are modeled on the network, how responsive flows are to network conditions, and the range of scenarios that can be evaluated. The remainder of the discussion in this document will use the term DTA to refer only to simulation-based DTAs.

Most DTAs, including all that have a high enough fidelity to model traffic management strategies, are simulation-based because simulation is needed to support the operational sensitivity required to achieve the increased modeling accuracy central to the mission of the DTA framework and implementation plan to be developed for CDOT. In a simulation-based DTA, traffic simulations are run iteratively where the travel times are output from the simulation and then used to model route selection by individual drivers in subsequent simulations. In the field, the desired route when departing at 7:00 AM may differ from the desired route when departing at 7:30 AM. Thus, the travel times used for route selection in the model are calculated for short intervals so that they vary by time of day and provide a more realistic basis for route selection. The model loops will be run over and over again until a sufficient degree of convergence is achieved.

Among DTAs, there are those that rely on mesoscopic simulation and others that rely on microsimulation or a hybrid combination of the two. Some mesoscopic models run on centerline planning networks while others use a more detailed representation of the road network and roadway geometry. A more detailed representation encompassing turn bays, islands, and intersection areas will have more accurate capacities and segment lengths resulting in greater fidelity in the model results. However, this means that planning networks cannot be used in their existing form but will require augmentation.

Mesoscopic simulation models predominantly use speed-density functions to simulate vehicle movements. More accurate mesoscopic models account for vehicle characteristics, such as length, but may fall short in modeling the combined effects of trucks and cars due to the use of a single speed-density function. Time steps from 1 second to 10 seconds are commonly used in mesoscopic simulation. Vehicle states (e.g., speed and location) are updated every time step as the density of traffic on the link on which they are traveling, or of the group of vehicles in the vehicle's vicinity, changes.

The primary attraction to mesoscopic models over microsimulation models is the faster running times that are owed both to the coarser speed-density representation of traffic flow and to the large time steps (step sizes in a microsimulation model are typically sub-second). It is also widely believed that mesoscopic models are less data-intensive on the model input side than microsimulation models, though this point can be debated.

It is also widely agreed that microsimulation entails a more accurate treatment of vehicle movements and operations. Hence, with the selling points of mesoscopic simulation clear, it is important to enumerate what is sacrificed in trade for those advantages, points that are far less widely recognized or appreciated:

- The shortest time steps will be most accurate, but most mesoscopic models achieve advertised running times with time steps much longer than 1 second. Longer time steps are generally associated with a minimum link length because of the requirement that a vehicle should not travel a distance greater than the length of a link on its path in one time step or risk introducing undue complexity in the vehicle movement models. For this reason, many mesoscopic models impose a minimum link length depending on the maximum speed a vehicle may travel on the link, and that length is often too large for realistic network representation, particularly in dense urbanized areas.
- Due to their time steps of 1 second or larger, mesoscopic models cannot simulate the actual workings of traffic signals. Instead, they calculate intersection delay using analytical queuing functions. These represent average behavior and tend to overestimate actual throughput by volume group. They also may fail to capture queue lengths and platooning effects accurately, particularly where signal timings are coordinated between closely spaced signals, which is a common signal timing strategy.
- Most mesoscopic models rely on rudimentary treatments of signalized intersections that do not capture the interaction between vehicle demand and green time that is key to actuated signal operation. Rather, most mesoscopic models accept only cycle lengths and splits (green + amber + red time) by movement as input, effectively treating all signalized intersections like pretimed signals. There are many reasons for this, but one reason is that mesoscopic DTA models are generally conceived and developed by travel demand modelers rather than by those who have experience in traffic signal timing concepts. This suggests that the choice of a mesoscopic approach and model platform should consider how signals are treated.
- Mesoscopic models require the specification of link capacities as an input. This can cause difficulties for several reasons. First, capacity is not a thoroughly defined or invariant metric. It can vary with speed as well as the particular circumstances of the links that are adjacent to any given link. Specifically, it can be difficult to pre-determine the capacities of merge and weave sections or acceleration and deceleration lanes.
- Many aspects of congestion are associated with lane-based conditions and behavior. In mesoscopic simulation, lane details are usually not present. In microsimulation models, lane choice and lane changing behaviors as well as merging and weaving maneuvers between lanes are modeled explicitly.

Microscopic traffic simulation is the gold standard for modeling traffic for many reasons. Among these are the most faithful and detailed representation of vehicle characteristics, driver behavior, and traffic dynamics.

The argument against microscopic DTA has largely been one of the required computing times. They have also been accused of being unforgiving when fed with unrealistic traffic volumes (e.g., from travel demand forecasts). With advances both in computing and modeling techniques, both mesoscopic and microscopic DTA have been shown to be practical. Recent reporting from transportation research, for example, offers evidence that microsimulation of wide areas is practical today (1).

Hybrid simulations, in which some parts of the network are simulated microscopically and other parts mesoscopically are a hedge to ensure the ability to perform region-wide traffic DTA with high fidelity. The hybrid model provides the flexibility to deploy very large models while retaining detail in key locations.

Table 1 summarizes the comparison between mesoscopic and microscopic simulation.

Table 1. Comparison of Key Aspects of Mesoscopic and Microscopic Simulation

ASPECT	MESOSCOPIC	MICROSCOPIC
Network	Some centerline networks; some more detailed representation	Ground-truth networks including turn bays, island, etc.
Traffic management strategies	Fidelity not high enough	Only microsimulation can accurately model traffic management strategies
Traffic flow model	Speed-density functions; requires link capacities	Car-following models, lane-changing behaviors are modeled explicitly, including in weaving and merging areas
Time Steps	Generally 1-10 seconds	Less than 1 second
Running times	Faster speeds are offset by loss of modeling accuracy	Reasonable running times even for regional DTA is achievable
Vehicle movement and operations accuracy	Lower than microsimulation	Better than mesoscopic simulation
Traffic signal operations	Cannot simulate signal operations; Estimates delay using analytical functions; Fail to capture full impacts of platooning and queues; All signals effectively operate as pretimed signals	Simulate traffic signal operations fully, including actuation, intermittent pedestrian phases, signal coordination, preemption, etc.

1.3 CURRENT TRAVEL DEMAND MODELS IN COLORADO

Travel demand models and, to a lesser degree, traffic simulation models are used in Colorado to plan for future transportation system improvements. MPO-level travel demand models are required tools that support the Federally mandated comprehensive transportation planning process. Colorado, like many states, has a statewide travel demand model that is used to address significant transportation system issues that cannot be addressed by regional models alone.

The current modeling platforms for the statewide model and MPOs are summarized in Table 2.

Table 2. Current Platforms for Colorado Planning Models

ORGANIZATION	TRANSCAD (CALIPER)	VISUM (PTV)
CDOT Statewide	x	
Denver Regional Council of Governments (DRCOG)	x	
Grand Valley MPO (GVMPO)	x	
North Front Range MPO (NFRMPO)	x	
Pikes Peak Area Council of Governments (PPACG)		x
Pueblo Area Council of Governments (PACOG)	x	

The statewide and DRCOG models are advanced-practice models. They are activity-based models (ABM) in that they model trips in tours as part of daily activity patterns. Individual trips by origin, destination, travel mode, and departure time intervals are among the generated outputs.

Currently, all travel demand models listed in Table 2 use static traffic assignment modeling procedures that cover various time periods of the day. This is the state of the practice around the country and the world; DTA has not yet evolved to the point of being a viable replacement for static assignments. Yet, static assignments do not capture the variations in traffic dynamics during each time period that underlie congestion or the factors that lead to it. These models also ignore or have difficulty with traffic management strategies, such as dynamic pricing on managed lanes, ramp metering, and traffic signals, all of which have a significant impact on traffic flow in the Denver metro region and elsewhere. Static assignment models are also insensitive to weather and terrain conditions that are material when considering dense flows within Colorado, such as those in the I-70 mountain corridor.

2.0 BENEFITS OF A DTA PROGRAM FOR CDOT

There are numerous potential benefits of a DTA program for CDOT. While there are direct benefits from the ability to perform better analysis of potential investments, there are also collateral benefits in terms of improved system performance and cost savings of various types. In what follows, we articulate what we believe to be the principal benefits that would accrue to CDOT and its stakeholders.

DTA models are the method of choice for ensuring that potential regional and corridor transportation improvement projects are properly assessed.

While still an emerging technology, DTA models bring a finer-grained temporal portrayal of transportation system performance than traditional methods and which is needed for impact assessment. DTA models can be sufficiently sensitive to reflect and help design traffic management strategies that are likely to be more effective and, in many instances, more cost effective than major construction projects. These tools are also needed to plan and operate managed lanes and other dynamically tolled facilities.

Because of their temporal fidelity, DTA models are ideally suited to assess greenhouse gases and hence to inform decision-making that contributes toward their reduction.

Accurate vehicle speed profiles form the basis for calculating energy consumption and emissions, and changes in speed distributions are used to evaluate the impacts of projects. Simulation-based DTA models can represent any possible mix of vehicle types and their characteristics, making it possible to evaluate energy and emissions savings from electric vehicles. They can also simulate strategies such as speed harmonization that are important tools for reducing greenhouse gas emissions. High-resolution output from DTA projections are the only reasonable means of estimating the air quality benefits from diverse initiatives.

DTA is likely to lead to fewer but better road projects.

DTA models are considerably more realistic than other models that are commonly used by planners to assess road projects. DTA models can be used to identify strategies for traffic management that will reduce the need for and desirability of new construction.

DTA provides a way to systematically evaluate a range of tolling, ITS, and other traffic management and control strategies.

DTA models are the only reasonable means of evaluating dynamic tolling and other dynamic traffic management strategies such as ramp metering, variable speed limits, and transit traffic signal pre-emption. Ramp meters are widely deployed in the Denver region. A tool for analyzing alternate metering algorithms and strategies would be a key advantage for CDOT. Furthermore, given CDOT’s commitment to use of managed lanes and to constructing a network of managed lanes in Denver, DTA models should be an integral part of the planning process for these facilities.

DTA models are the appropriate tool for managing operations and refining tolling strategies on managed lanes.

DTA models are used elsewhere by toll road concessionaires and operators for the purposes of refining tolling strategies. CDOT can derive economic benefits from more accurate analysis of tolling strategies. Revenue enhancement will be a direct result of using a DTA to manage tolling and related operational strategies. Through the Colorado Transportation Investment Office (CTIO), CDOT has a direct financial interest in the revenues generated from its owned and operated facilities. A regional DTA simulation model can be used to optimize revenues as it is by other concessionaires and operators around the country.

An important application of DTA is in the design of solutions for maintenance of traffic (MOT) when significant road closures are necessary.

Investment in a regional DTA would likely be justified by the benefits it would confer on MOT activities alone. Reducing travel delays from work zones can be achieved with suitable simulations that are sensitive to the re-routing of traffic. A DTA can predict the routing effects of lane closures and identify the best detour routes when those are needed.

DTA models should enhance the safety of roads under CDOT purview.

Safety analysis relies on properly archived incident data with proper characterization of context. DTA models and supporting data provide more accurate measures of exposure and traffic levels, affording a more incisive method of identifying problematic locations. In particular, understanding congestion points, traffic conflicts, and locations of dramatic speed changes are an important means of identifying locations where safety improvements are warranted. The simulations used by DTA also permit direct linkage to Highway Safety Manual (HSM) calculations and geospatial accident prediction.

DTA model outputs provide support for conventional traffic analysis and simulation.

DTA models can serve as cost-saving feeders of traffic analysis and simulation studies that rely on many of the same modeling inputs and data sources. DTA models can support traffic simulation models in a way that is more relevant and accurate than deriving the same information from simpler traffic models and/or from travel demand models that operate with a much lower level of fidelity with respect to geometry and traffic flows. Single-period analysis tools that are commonly used in practice for traffic signal timing studies (e.g., Synchro) are often misused for analyses for which they are not designed nor intended. Such a practice will give poor estimates of capacity and delay and will yield biased results when compared to multi-period (i.e., dynamic) analysis (2). A wide-area DTA can also provide essential data for many locations and reduce the need for and cost of some traffic data collection.

DTA models should be superior substitutes for static traffic assignment models widely used in regional travel demand models.

Moreover, traditional static traffic assignment tools ignore the finer temporal resolution in trip-making patterns that are key to activity-based models (ABM) like the ones that CDOT and the Denver Regional Council of Governments (DRCOG) use. DTA preserves and respects the representation of travel by half-hour or hourly time periods that ABMs and other modeling tools provide, whereas static assignments aggregate trip-making patterns over much longer time periods.

Travel choices are made by considering and comparing travel alternatives as they exist at a particular departure time. A better understanding of travel determinants and improved predictive ability come from considering how auto competes with alternative modes for travel to specific destinations by time of day. Use of travel times that have been averaged over multi-hour time periods biases model parameter estimation and model predictions. Properly capturing the competitiveness of alternatives to auto travel is best done when congested auto speeds are known and used in analysis.

Adding accurate dynamic travel times to travel demand models will improve their accuracy and usefulness and help identify a better mix of modal transportation services to serve mobility needs. This may be particularly important in improving transit planning going forward.

Traffic simulation is the principal analysis method for performing traffic operations impact assessments.

When traffic management strategies that will impact travelers' route choices are contemplated, DTA is the appropriate method of analysis because its purpose is to simulate operations iteratively until routes are chosen based on information that is consistent with travel conditions experienced in the model. Thus, just as increased

DTA deployment promises to improve transportation planning methods and practices, so too will a DTA initiative inevitably lead to improved traffic simulation analyses as a byproduct. If well maintained and made available to consulting partners, regional and corridor DTA models can greatly reduce the costs of using traffic simulation to evaluate and refine projects by avoiding duplication of effort. The state of the practice commonly involves separate analyses of every project with little or no continuity between, or carryover from, prior analyses.

DTA models are valuable in communicating with the public to explain projects and illustrate their benefits.

Two-dimensional and 3D dynamic visualizations are part and parcel of successful DTA implementations. As such, they offer CDOT an opportunity to more inexpensively produce animations that better engage public involvement and stakeholder input than do the charts and figures of traditional modeling tools.

DTA benefits from and contributes to numerous data initiatives that provide informative portraits of system characteristics and performance.

Because of their focus on the time-varying nature of traffic, DTA models are a better complement to data products that are used to monitor system performance and mobility. Integration with ongoing and future data initiatives is thus an important consideration in the implementation plan.

Simulation-based DTA models are the only realistic means of understanding connected and autonomous vehicle (CAV) impacts and planning for future implementations.

Planning for technological advances such as CAVs will become increasingly important for State DOTs going forward. DTA can also be instrumental in planning for an electric vehicle future, especially with respect to location of public charging stations.

3.0 A VISION FOR WIDE-AREA, HIGH-FIDELITY DTA FOR COLORADO

Our overall vision is to create a **digital twin** of major Colorado road facilities rich enough in geographic, geometric, operational, and behavioral detail to support analysis of transportation investments and to support transportation systems management in both planning and operations.

The essential concept of a digital twin is to provide a means of simulating future realities without having to incur their actual costs or having to wait many years in order to ascertain and/or understand their likely impacts.

The digital twin would be both extensible and supportive of windowing for subareas and corridors and would be a significant resource for CDOT activities while at the same reducing the costs of performing the same analytic work**.** While there can be various ways of implementing this vision, it must be ambitious enough to achieve the benefits that we have outlined. It must also provide for and welcome future enhancements to be responsive to evolving transportation technologies.

In the simplest terms, dynamic traffic models are warranted when transportation projects and/or management measures influence travelers' route or travel mode decisions. Even some of the simplest decisions such as those aimed at retiming a traffic signal are more appropriately analyzed with a dynamic, multi-period model. At the other end of the spectrum, major construction projects cannot be meaningfully analyzed and evaluated without considering how travel patterns and routes will change.

For major new transportation technologies such as connected and autonomous vehicles, dynamic traffic models are required to capture a broad array of changes in system performance and associated behavioral adjustments. Some of these impacts will require advances in travel demand models but even those will be anchored by the performance afforded by transportation supply and its improved efficiencies.

There can be no question that some of the most pressing planning and engineering questions will be posed by new technologies, new services, and future economic conditions. The digital twin will provide a reasonable way forward to contemplate, simulate, and analyze a great many future eventualities.

A central consideration for accomplishing this vision is what type of DTA approach to take given the range of factors described in the Introduction: relative advantages and disadvantages of mesoscopic and microscopic simulation, compatibility with regional travel demand models in Colorado, etc. Below we list key criteria accounting for effectiveness in application, practicality of implementation and use, and other relevant factors for executing the digital twin vision.

3.1 DEMONSTRATED VIABILITY

There are many types of DTA models that have been proposed but many fewer that have seen successful deployment. The DTA approach should have demonstrated viability and thus be of low risk. This will also ensure that simulation studies performed for CDOT are undertaken with proven solutions and do not become expensive research projects. Sustained and successful implementations should be achievable without requiring the software developer’s involvement in the project.

3.2 SUFFICIENT FIDELITY

A DTA for CDOT should have sufficient fidelity and detail to analyze traffic operations and be able to evaluate the traffic management strategies that are important and relevant in Colorado. As described earlier, microsimulation models are needed to evaluate many operational strategies. Hence, if mesoscopic DTA is to be part of the approach, then the mesoscopic DTA should lend itself either to (a) subarea analyses that can produce subarea models for microsimulation analysis or (b) hybrid mesoscopic-microscopic simulation.

There are precedents in current practice for both approaches to multi-resolution DTA. The subarea approach allows a regional DTA to be leveraged to produce model inputs, including dynamic estimates of traffic demand, for microsimulation of a smaller study area. Static assignments of the kind used by most MPOs can be used to produce similar inputs for microsimulation studies but produce demand estimates that require significant and time-consuming demand adjustments because of the widely recognized deficiencies inherent in static models, namely their inability to represent queuing and spillback.

A multi-resolution approach to DTA that tailors model fidelity and scale to the purpose or application is consistent with emerging practice and FHWA initiatives. The hybrid modeling approach allows a DTA to be run in the regional DTA without having to extract subareas. Rather, the study area around the project or projects of interest are simulated microscopically and the surrounding regions mesoscopically. This approach is generally preferred to the subarea approach because of the efficiencies that can be achieved when all steps of the analysis can be performed in a single model without the expenditures in time and resources to develop a second, albeit smaller, model. These additional expenditures can increase the cost and schedule of the analysis and will inevitably lead to inconsistencies between predictions made based on the regional DTA and those based on the subarea model. However, if the subarea model will be the principal decision-making tool and the DTA model a steppingstone to faster development of better subarea models, then these inconsistencies may be acceptable.

3.3 ACCURATE REPRESENTATION OF ROAD GEOMETRY AND GEOGRAPHY

It should provide an accurate representation of road geometry and geography so that inaccuracies are not introduced into the models from those conditions.

It would be advantageous if the DTA approach makes effective use of GIS-based data and has some form of integration with existing GIS systems. This would enable the model to readily absorb data from a wide variety of sources including traffic counts, the National Performance Monitoring Research Data Set (NPMRDS), commercial speed data, navigation systems, and big data from location-based services.

It is also worth mentioning that the ease and the rapidity with which network editing can be done is also important as it makes it practical for quickly developing simulations of emergency conditions. Development and maintenance of a statewide, simulation-ready road network, which will also be among the recommendations of the framework and implementation plan, will allow for simulations and DTA analyses to be developed quickly and cost-effectively.

3.4 DATA WAREHOUSE

Accompanying the DTA should be a data warehouse for traffic data that permits capture and reuse of data collected for traffic simulation and produced as output from traffic simulation studies. This will save costs and improve forecasting accuracy when maintained on an ongoing basis.

3.5 PROVIDE SUPPORT FOR COLORADO-SPECIFIC MODEL CONCERNS

Successful DTA implementation will address salient characteristics of traffic flows in Colorado as they are impacted by terrain and seasonal climate factors as well as other key aspects of Colorado road networks and network management. Specifically, it should be able to model:

1. Individual managed lanes and a network of managed lanes with dynamic tolls.
2. Impacts of the current ramp metering algorithm as well as alternative ramp metering strategies.
3. The effects of highly variable terrain as it exists in Colorado.

3.6 SCALABLILITY

Region-wide DTA models pose various challenges due to the scale of models required. The DTA approach should be scalable to model any MPO region or major corridor in Colorado. Clearly, the DRCOG region is the largest and the one in greatest need of a DTA. Practical running times to convergence will be needed.

3.7 INCORPORATE AND SUPPORT TRAFFIC SIMULATION STUDIES

Some of the benefits of a DTA will come from its ability to incorporate and support traffic simulation studies. Simulation studies should be much more cost-effective to develop with the availability of a preexisting DTA. Hence, the approach should make provision for being able to warehouse prior simulation data inputs and outputs.

3.8 EASY INTEGRATATION WITH TRAVEL DEMAND MODELS

Given the future forecasting emphasis of project evaluation, the DTA approach should provide for integration with existing travel demand models. This should be a two-way integration so that the DTA can potentially take the place of the static traffic assignments in the travel demand models. A more seamless integration between simulation analyses and other modeling tools used in the region will translate to improved collaboration between agencies and consistency between decision-making tools.

Compatibility with emerging and state-of-the-art planning models, such as activity-based models like DRCOG’s FOCUS, is also important. A well-designed DTA for the Denver region, for example, will directly simulate the trips forecast by FOCUS, preserving and leveraging the DTA model’s increased temporal fidelity over more traditional travel models.

Apart from that temporal coherence and the ability to develop reasonable travel times from them, the DTA should flag impossible travel patterns and congestion levels. Having extensive experience with ABM-DTA integration, we know that one frequently encountered problem is that ABMs are typically developed and calibrated using travel times (i.e., "skims") from static models. This has the effect of underestimating congestion and overestimating road capacity, in turn leading to more and faster travel than would be feasible in reality, especially during the peaks of the peak periods.

An objective measure of the readiness of a DTA for integration with an ABM is whether the DTA provides skims that are consistent with real world measurements of travel times and does so for different time intervals within a peak period.

3.9 PRACTICAL RUNNING TIMES

Practical running times are another of the many important topics that will be addressed in the DTA framework and implementation plan. Just as a fast DTA is of little value if it cannot address the traffic management concerns of CDOT and other regional agencies, the most accurate DTA is not useful if it cannot be run in reasonable times. Hardware recommendations will be made in the implementation plan to ensure successful deployment.

3.10 OTHER POTENTIAL OBJECTIVES

As the shape of the DTA framework and implementation plan comes into better view, other objectives will be considered, including but not limited to:

1. Data availability and the ongoing data burden
2. Affordability
3. Ease of use

4.0 TECHNICAL APPROACH

Based upon the above DTA objectives described above, the logical approach is to develop a mesoscopic regional DTA with capabilities for hybrid mesoscopic and microscopic simulation. This approach has the following merits:

1. All major vendors of traffic simulation software offer some form of this multi-resolution capability.
2. Multi-resolution modeling is on the rise nationally. FHWA is currently funding an effort to develop guidance for multi-resolution modeling, guidance that may benefit and support practitioners in Colorado working with multi-resolution DTA.
3. By choosing a flexible, multi-resolution approach, practitioners will be able to start with a baseline mesoscopic model that can be run regionally with modest computing power and in modest running times yet still retain the ability to achieve accurate operational simulation for projects or subareas that require lane-level detail or more fine-grained treatment of the operational performance of different types of vehicles on different types of geometries and terrain.

There are many common elements and requirements that are needed if a DTA is to be detailed enough to be useful for traffic management and project evaluation. We review these basic requirements so that they may provide a foundation for discussions with CDOT on elaborating a recommended approach.

4.1 BASIC REQUIREMENTS

The basic requirements discussed below are fundamental to a DTA framework and hence can be treated as a baseline checklist for a DTA approach.

Temporal Resolution

The DTA approach should enable modeling origin-destination (O-D) flows by 15-minute or shorter time interval. This has typically been the longest time interval used in DTA implementations. While an argument can be made for 10-minute demand intervals, these have not been shown to be required. Also, because 15-minute time intervals are common in highway capacity and other traffic analysis tools, this resolution has the added benefits of being readily comparable to analyses performed with other methods that are used in the traffic engineering community.

Intersection Level of Detail

All DTA models have some form of treatment of intersections and interrupted flow facilities. It is important that each intersection in the model be characterized by its type. For signalized intersections, that information should include the type of signalization (e.g., pretimed or actuated). Basic signal timing information should also be part of a DTA model so that the capacities of different lane groups on different approaches can be modeled to a reasonable degree. The form and level of detail in traffic signal timings will vary between DTA software platforms, with especially limiting representation in some mesoscopic models. Hence, the ability to microsimulate subareas or to choose microsimulation for some parts of a hybrid DTA will be especially important for projects in which signal operations are important.

Dynamic Shortest Paths

Another key component of a DTA is the ability to compute dynamic shortest paths. The dynamic shortest path algorithm is a basic construct of the route choice model in a DTA, or at least of the path choice set enumeration process, that process by which the DTA produces the paths from which a driver can choose. Route choice models in some DTAs require that such a choice set first be created. Whatever the route choice model, a DTA should be able to compute dynamic shortest paths for each O-D time interval, and those should be compare and validate well against recommendations of navigation services and GPS traces. In other words, the shortest path should be based on the departure times of trips and the link travel times that a vehicle will experience given that departure time. This is fundamentally different than in a static model in which link travel times do not vary with a long period and paths chosen are not sensitive to their departure interval. Not only will the DTA be required to compute dynamic shortest paths, but it must also be able to compute large numbers of them efficiently.

Route Choice Modeling Requirements

Different DTA platforms take different approaches to route choice. Some may rely solely on dynamic shortest paths while those that require an explicit path choice set typically employ discrete choice models to predict route utilization. A viable DTA will have a robust and demonstrably valid route choice model. While all route choice models in a DTA will take expected travel time as an input as well as tolls, other variables may be relevant. These other variables may include road class, the presence and number of traffic signals, and travel time reliability. While all DTAs will be able to model route choices made before traveling, if the DTA is to be used to evaluate conditions of non-recurring congestion or some advanced travel demand management strategies, then the DTA must also be able to simulate changes to one’s path en route.

Iterative Path Assignment and DTA Convergence

A DTA solution must be computed iteratively, wherein each iteration entails a simulation of the entire analysis period. Vehicles may change their routes from one iteration to the next to improve their travel times. Consequently, the experienced travel times may change by time interval on each link. Consistency between the travel times used to assign trips to routes and those experienced after doing so is a key aspect of a DTA and is most typically referred to as convergence. Without good convergence, the results of the DTA will be misleading and unreliable. However, a common challenge in achieving convergence suitable for comparing or ranking project alternatives is the stochastic nature of traffic simulation, whether mesoscopic and microscopic. Each simulation is likely to vary in its detailed outcomes. To counter the probabilistic nature of the simulations, some form of averaging is typically employed. Different convergence metrics and strategies are employed in different DTA software platforms. Which convergence approaches are robust and practical will depend on the model and may need to be established in empirical work.

Practical Running Times

Given that DTA is iterative and requires multiple simulations of the same period, the number of iterations required to achieve reasonable convergence will be a key determinant of running times. Typically, to achieve DTA convergence will require 30 to 50 iterations. Model run times will be directly proportional to the time it takes to perform a single simulation.

Validation Against Observations

Convergence, while required, is not alone a figure of merit for a traffic simulation or DTA model. DTA models, like other transportation models, must be validated against observed measurements. For a base case model, the objective of the DTA should be to reproduce travel speeds and traffic volumes. O-D travel times should be close to those that are measured in the field. It is especially important that the model show congestion at the locations and during the time intervals in which it is observed.

Select Link or Select Zone Analysis

Generally, DTA models should be expected to provide select link and zone analysis. This is straightforward when all the paths utilized in the DTA solution are saved for query or visualization post-DTA. Without select link or select zone analysis tools, DTA models become black boxes that are difficult if not impossible to interpret or to wield effectively. It is also not unreasonable to validate that the paths utilized in the DTA solution are a reasonable reflection of those that are used by actual travelers. Validation against observed data of this kind has become gradually easier in recent years given the availability of sensor data and data on vehicle movements and network speeds.

4.2 ADDITIONAL REQUIREMENTS

The basic requirements described above relate to the function and features of the DTA itself. However, there are factors external and peripheral to the DTA that are equally important to successful DTA model development, calibration, validation, application, and maintenance. The discussion that follows explores these additional requirements for a DTA approach. Assimilation of these requirements into the framework will lay groundwork for time and cost savings in traffic studies that leverage the regional DTA.

Network Data

There are common, minimum data requirements for any DTA implementation regardless of approach. First among these is an accurate regional network. Whether or not the DTA software uses a native GIS representation for the DTA network, an accurate GIS network should be a basic requirement and is one that is easy to fulfill given the wealth of GIS data available to CDOT and throughout Colorado.

Where regional DTA has been attempted, common practice is to start with a network derived in some fashion from a regional planning network developed and maintained by the state or MPO. A DTA network, however, often needs more detail than is needed or desired in a planning network. This is because some streets that are not of a high enough functional class to be included in a planning network may still be important from the perspective of operations (e.g., if the street intersects with a street in the planning network at a signalized intersection). Additional detail may also be needed to achieve reasonable loading of traffic from trip origins (e.g., traffic analysis zone centroids) onto the DTA network. The amount of detail that must be added to the DTA network will vary with the planning network.

Further, lane-level detail may be important. For instance, the number of lanes and the locations at which lanes are added (e.g., at turn bays) or dropped (e.g., at acceleration lanes) should be represented explicitly in order to accurately model storage capacity, which will affect the severity and extent of queuing and queue spillback. In some DTA models, lane geometry, such as lane widths, can be relevant. In parts of a model that will be simulated microscopically, there will be a need to specify the lane geometry.

Conversely, mesoscopic models generally require that the capacity of a link be specified as an input. This is a considerable but manageable burden. The capacity of a link is not independent of the geometric context in which it exists. Links in merging and weaving areas, for example, are likely to require capacity adjustments because the assumption that they have the same capacity as a basic freeway segment with the same number of lanes does not hold. Some of the requisite adjustments may possibly need to be volume-dependent if the mesoscopic traffic flow model is not sensitive to, for example, the ratio of weaving to total traffic in a weaving area.

Planning Model Integration

As previously mentioned, a critical consideration for CDOT in designing a DTA approach is proper integration with existing MPO travel demand models in Colorado. All of the models used by MPOs in Colorado are all capable of exporting their trips by origin, destination, and time period. Hence, this mechanical linkage will not really be at issue in most cases. The challenges in utilizing demand from produced by a travel demand model lie in preservation of demand detail and augmenting it with additional information. The detail includes flows by vehicle type, especially trucks and buses that have higher passenger car equivalents in traffic. Taxis and ride share vehicles may also be significant in some metropolitan areas. Detail that must be mined from other data sources (e.g., surveys, counts, prior studies, etc.) and used to augment the demand estimates before they are suitable for input to DTA include distribution of departures over smaller time intervals and a finer-grained distribution of value of time.

DTA for ABM integration presents additional challenges if the DTA is to simulate trips according to their schedules as determined by the ABM. The DTA must also keep track of the arrangement of trips in tours by the same individual and vehicle and ensure that trips do not depart before prior trips and activities have been completed.

Two-way integration requires providing ease of access of DTA output to the planning model so that it can be utilized there. Ideally, there would be no undue computational burden involved.

Value of Time Distributions

When there are tolled facilities in the region, the DTA must have a reasonable representation of drivers' willingness to pay if the DTA is to be useful for predicting the use of managed lanes or other tolled facilities. This is usually accomplished with value of time (VOT) data. The DTA should make provision for flexibility in value of time distributions by type of user and trip type.

Demand Reconciliation and Dynamic O-D Estimation

The trips predicted by a travel demand model will not ordinarily be consistent with those in a calibrated traffic simulation or DTA model. One key reason is that they are based on consistency with a completely different set of assumptions on travel times and route choices. Every simulation model, including those embedded in a DTA, needs to reckon with this inconsistency, but a much more difficult problem is estimating the O-D pattern for each 15-minute time interval that is modeled (3). This is a core challenge and one that is not avoided by simply factoring overall period trips by time interval with varying proportions. Every DTA model of sufficient quality will require dynamic O-D estimation for the base case scenario. Whether this is a built-in function or is done separately (i.e., in software platform separate from the DTA), it is a necessary aspect of DTA implementation.

Speed-Density Function Calibration

Mesoscopic simulation-based DTA models typically move vehicles according to speed-density functions. These need to be calibrated for different road classes and potentially different conditions, especially those associated with weather. Also, for a DTA in Colorado, the effect of road elevation and grade will be critical in some parts of the state. There is a small literature on these topics that could provide a basis for the needed effort. In the framework and implementation plan, we will seek to identify the data, which CDOT may already possess, that are needed to calibrate speed-density function parameters.

Traffic Signal Timings and Traffic Signal Optimization

DTA models require some level of detail in traffic signal timings. Some models rely simply on green times and cycle lengths for each permitted movement while others attempt to faithfully represent actual signal timing plans, including those for actuated signals. Because of CDOT's investment in recent years in the TransSuite Advanced Transportation Management System (ATMS), which centralizes the management of traffic signal timing plans, it may be possible to retrieve up-to-date signal timing plans directly via the system's existing data portal and web service interface. This automated retrieval and update process would ensure model currency and accuracy and would extract added value from prior CDOT's ATMS investments. While actual timings are preferred, they will not always be available. Consequently, they will need to be estimated or created for the model. This will typically be the case for future scenarios for which signal timings will need to be created or re-timed due to increased or otherwise different (e.g., diverted) demand. Traffic signal optimization can be built in to the DTA or can be performed externally using different tools.

Multiple Base Case Models

Normally, one has a reference base case model that is used in forecasting. The base case typically refers to a current or recent year and is modified when modeling future scenarios. Because DTA models are sensitive to more varied conditions, it may make sense to have base case models for different seasons of the year and for weekend and weekday scenarios.

Validation Data

The DTA models of the future will benefit from the greatly expanded data available for validation. In addition to the traditional and ongoing traffic counting programs in Colorado, speed data by five-minute interval is available for many road locations. The NPMRDS data provided by FHWA to the states and MPOs has this information for every day of the year referenced by Traffic Message Channel (TMC) segments. Similar data is available commercially for a broader set of roads from HERE and INRIX. The INRIX XD data is link-based and could be very helpful in validating DTA models.

There are other sources of data from GPS traces from vehicle and cell phone apps that are expected to be useful for model development and validation in the future. Data from the American Transportation Research Institute (ATRI) provides the routes used by a significant fraction of the over-the-road trucking fleet.

Model Sensitivity Testing

It is a straightforward extension of established planning and microsimulation model practice to seek to validate a DTA model against the kinds of validation data just described. However, a DTA model should also be validated by examining its predictions when changes are made to the input transportation demand and supply. This can be done by making forecasts for short term changes and comparing the results to those observed. This exercise may also involve inspecting forecasted longer term and unobservable changes for reasonability.

Microscopic DTA

To obtain the greatest value from the investment in a regional hybrid DTA model, it should be possible, at a minimum, to develop microsimulations of subareas. In the recommended hybrid mesoscopic-microscopic DTA approach, the subarea need not be simulated separately from the regional DTA. Rather, traffic is microsimulated in the study area and mesoscopically in the rest of the region. However, it will not be practical or necessary to simulate the entire region for every project. This does not mean that DTA will not have an important role to play in the analysis of the subarea. DTA may still be the best tool for estimating the route diversion that may result from a project.

Microsimulation studies typically do not involve DTA even when estimation of diversion is a requirement of the analysis. While the state of the practice is beginning to see more such applications for DTA, the more common practice is to assert the nature and magnitude of diversion based on little more than analyst judgement or to rely on static assignments. This state of the practice is due to a variety of factors, including but not limited to the relatively recent availability of commercially viable DTA, a lack of training and education, the perception that assignment of any kind belongs to the planning and not the engineering domain, and slow uptake of new tools and ideas (i.e., professional inertia).

While we are not recommending that the ability to run DTA in the microsimulation model be a requirement of the DTA approach, a DTA that can be run microscopically for large areas has many benefits and should be preferred in most cases because of the accuracy and consistency that such an approach can provide. If the travel times on which drivers choose their routes in the microsimulation model are the same travel times that are experienced in the microsimulation, then the DTA has a better chance of achieving the consistency and convergence previously described.

Documentation and Training

When any model is to be used by others, it should be fully and accurately documented. This is especially important for an advanced model like a DTA because users of the model cannot be assumed to be familiar with many of the issues that are involved and with the decisions they are likely to encounter in model application. Similarly, DTA training should be provided on a periodic basis as staff turnover should be expected at CDOT and consulting firms.

5.0 PLAN DEVELOPMENT PROCESS

As we have explained in the technical approach, not all DTA methodologies can fulfill the digital twin vision described earlier in this report. In addition to having a sound approach, a carefully designed and diligently implemented DTA plan is needed to achieve the stated benefits. A plan development process was conducted in addition to the technical work done to support the recommended technical approach. The plan development process had several key elements. The first element entailed identification of stakeholders and elicitation of their views on desired DTA solutions. Interviews were conducted with key individuals, and a workshop was held to describe technical aspects of DTA models and their implementation. A series of further discussions were conducted with CDOT to refine our recommendations. We also discussed various implementation plan issues to obtain guidance from CDOT.

5.1 STAKEHOLDER INTERVIEWS

In CDOT, we spoke at some length with Paul Scherner, Erik Sabina, and Ben Acimovic. There is general recognition that an available DTA tool would be of considerable value if it were practical. We also spoke with Nick Farber, head of the Transportation Investment Office.

From Region 1, Mr. Scherner has perceived the need for a DTA for many years, which is why it is not a coincidence that he was the champion of the study that produced this document. An initial motivation expressed by Mr. Scherner was the need for a tool that would be comprehensive enough to assess the broader geographic impacts of very localized improvements. He also felt that it would be very efficient to have an available tool that could take the place of numerous separate models and studies and that bringing some consistency and technical improvements to separate studies would save time and money. Lastly, Mr. Scherner understood that DTA was a superior tool for roadway analysis and that it resolved inconsistencies associated with single-shot simulation models that perform one simulation without iteration to update route choices based on simulated congestion patterns.

Representing the CDOT travel modeling group as one of his responsibilities, Mr. Sabina has similarly appreciated the case for dynamic transportation models. As the main mover behind implementation of activity-based travel demand models in Colorado, first at DRCOG, and then subsequently at CDOT with the statewide model, Mr. Sabina has been committed to using more advanced tools that address policy and planning needs. Mr. Sabina has also built a small modeling group in CDOT that has research backgrounds in travel choice models and DTA in particular. Both Juan Robles and Scott Ramming did relevant Ph.D. thesis work on route choice and DTA.

In our discussions, Mr. Sabina stressed the need to connect a DTA modeling effort to support of CDOT policy initiatives. He also provided input on CDOT management priorities.

Historically, CDOT Transportation Systems Management and Operations (TSM&O) staff have not been deeply involved in modeling, but that is changing. In his new role in TSM&O at headquarters, Mr. Acimovic expressed interest in building analytical capabilities within the operations group at CDOT and conducted a survey of the use of traffic analysis tools by CDOT staff. In our first discussions, Mr. Acimovic suggested that a benefit-cost analysis be applied to a DTA Program and that that analysis could be used to justify the necessary investment.

A DTA is a natural tool to support the TSM&O Office objectives. **The mission of TSM&O is: "To systematically improve travel time reliability and safety on Colorado highways through technology, innovative programs and strategies, targeted traffic management activities, and safety improvements to maximize the return on investment of transportation funds."** More specifically, system management initiatives are intended as an alternative to expensive construction projects for which funding is no longer available nor are construction projects thought to be effective in reducing congestion. Evaluation of these initiatives is best done with an appropriate dynamic traffic model.

Given the limited use of traffic analysis tools at CDOT, the software survey only indicated fairly widespread use of Synchro and limited use of other tools. Interest was expressed in software for freeway analysis, a finding that is not surprising given CDOT’s responsibilities. Survey respondents also opined that traffic analysis should be performed by both the Regions and Headquarters, and that training would be welcome in part to strengthen review of consultant work. Neither the survey nor the open-ended responses addressed the need for tools to address emerging technologies although those are likely to be rather important in the future.

Recently, Elena Farhadi joined CDOT and began participating in our project meetings. Ms. Farhadi has a background in traffic engineering and has experience with simulation modeling. Her presence adds to CDOT’s ability to carry out a DTA program in the future.

DRCOG has been an active participant in this project and a supporter of its goals. As the largest MPO in Colorado and the MPO with the most significant mobility and traffic challenges, DRCOG has a significant stake in any major modeling initiatives. Steve Cook and Robert Spotts have represented DRCOG in our meetings. DRCOG has a fairly advanced travel demand model, but the model’s traffic assignment is one of its weaker elements. From an objective technical perspective, it cannot be used effectively to model the network of managed lanes that is being implemented. Also, it is not sensitive to any initiative involving traffic signals or ramp metering. A DTA for the region would address this and would provide a superior tool for analyzing future mobility and specific projects.

The DRCOG representatives identified accurate geometry as an important need in any future DTA implementation. The lack of lane-level and intersection detail in a prior exploration of DTA by DRCOG was cited as a critical shortcoming. Other DTA platforms than the one tested by DRCOG support highly detailed lane-level models of roadway infrastructure. Apart from a key role in long term transportation planning, a DTA would also support and upgrade the simulation studies that are regularly performed for DRCOG and/or the City of Denver.

Communications with the various stakeholders both independently and in a group setting conveyed unanimity in support of a DTA resource if it can be successfully implemented.

5.2 SCAN OF DTA PROJECTS NATIONWIDE

A second element was a brief review of experiences with simulation and DTA in Colorado and elsewhere. DTA models have been used in Colorado by Caliper, the authors of this document, in work on both the I-70 mountain corridor and the investment grade C-470 study and were subsequently applied in several simulation projects performed by other consultants for CDOT.

A scan of high-fidelity, wide-area DTA projects outside of Colorado was conducted. DTA models used for demand modeling but not suitable for operations planning and analysis were omitted from this scan. Apart from Caliper's work with its own DTA platform TransModeler, the scan did not reveal more than one additional implementation, and that was for a special-purpose system and is not intended for general use.

Two Caliper wide-area DTA projects illustrate some of the basic concepts of wide-area DTA. The first of these was a regional microscopic DTA built first for Central Phoenix and then expanded to include all of Maricopa and Pinal Counties for the Maricopa Association of Governments (MAG). Following a practice alluded to in this report and recommended in the technical approach, the regional DTA for Phoenix was used subsequently to derive subarea models for microsimulation analysis of capital improvements on the I-10/I-17 Spine Corridor, specifically the addition of an HOV lane on I-17 and the geometric reconfiguration of multiple interchanges. The same model was also used to evaluate direct connection ramps for use by a proposed rapid bus service feeding the downtown area.

The DTA model was used by MAG staff and by numerous consulting firms without help from the model developer to evaluate other projects throughout the region (5) and continues to be used to support ramp metering analyses for the Arizona DOT (ADOT).

For Michigan DOT (MDOT), Caliper has developed a mesoscopic simulation of a wide area of Southeastern Michigan including the greater Detroit metropolitan area. Much like what has been suggested for CDOT, this is model intended to support more detailed, microscopic simulation of specific major capital projects. Since its development, it has been used by MDOT personnel in-house to answer MOT questions during an Interstate resurfacing project and to evaluate the impacts of road diet initiatives.

As a veteran of numerous DTA projects, Caliper's perspectives have evolved significantly over time. While demonstrating the practicality of these tools, we have developed an understanding of the complexities involved and the continuing need for further research and development.

We continue to believe that microsimulation is far more realistic and better defined than mesoscopic simulation and that microsimulation-based DTA should be used whenever possible.

5.3 IDENTIFICATION OF PLAN ELEMENTS

A third component of the plan development process was the identification of the requisite plan elements and their important characteristics. We used our experience to describe the essential elements of an effective DTA solution. We considered our prior technical recommendations, inputs from stakeholders, funding requirements, and roles and responsibilities. Lastly, we created some illustrative examples and performed some limited experiments to validate our recommendations and to provide illustrations of practicality and utility of wide-area DTA models.

6.0 PLAN ELEMENTS

Below, we discuss the key DTA implementation plan considerations and work elements with recommendations where appropriate.

6.1 RECOMMENDED TECHNICAL APPROACH

Choosing the right technical approach is pivotal to realizing the benefits of DTA. This should happen early in the implementation process and should follow a robust and inclusive process that engages the model's various stakeholders and accommodates, to the extent possible, their modeling and analysis needs and requirements. The importance of this consensus-building step for the long-term viability of the model cannot be overstated. The elements and factors around which the technical approach should be designed are enumerated in the Technical Approach presented earlier in this report.

6.2 BASELINE MODEL DATA REQUIREMENTS

DTA models have specific baseline data requirements for them to be reasonable representations of traffic flow phenomena. These may be thought of as the minimal data needed to develop a base case model for a given year.

These requirements begin with a suitably detailed representation of the road network.

A lane-level representation of the road network is necessary for microscopic modeling of subareas and can be a requirement of higher-fidelity mesoscopic simulation models. This will include representation of intersections and permitted movements therein. In our experience, the lane-level representation is preferred to the alternative, centerline planning networks, which lack crucial detail such as turn bays and acceleration and deceleration lanes that fundamentally contribute to queue storage and increased capacity.

The broad availability of satellite and aerial imagery has greatly facilitated the development of lane-level networks for use in simulation and DTA modeling. Additional information on terrain is also available making it possible to capture realistic elevation data for the network. Coding of future projects can be done in various ways with preference given to use of engineering drawings and maps when they are available.

Caliper has completed lane-level mapping of both the DRCOG (Figure 1) and statewide (Figure 2) model planning networks.

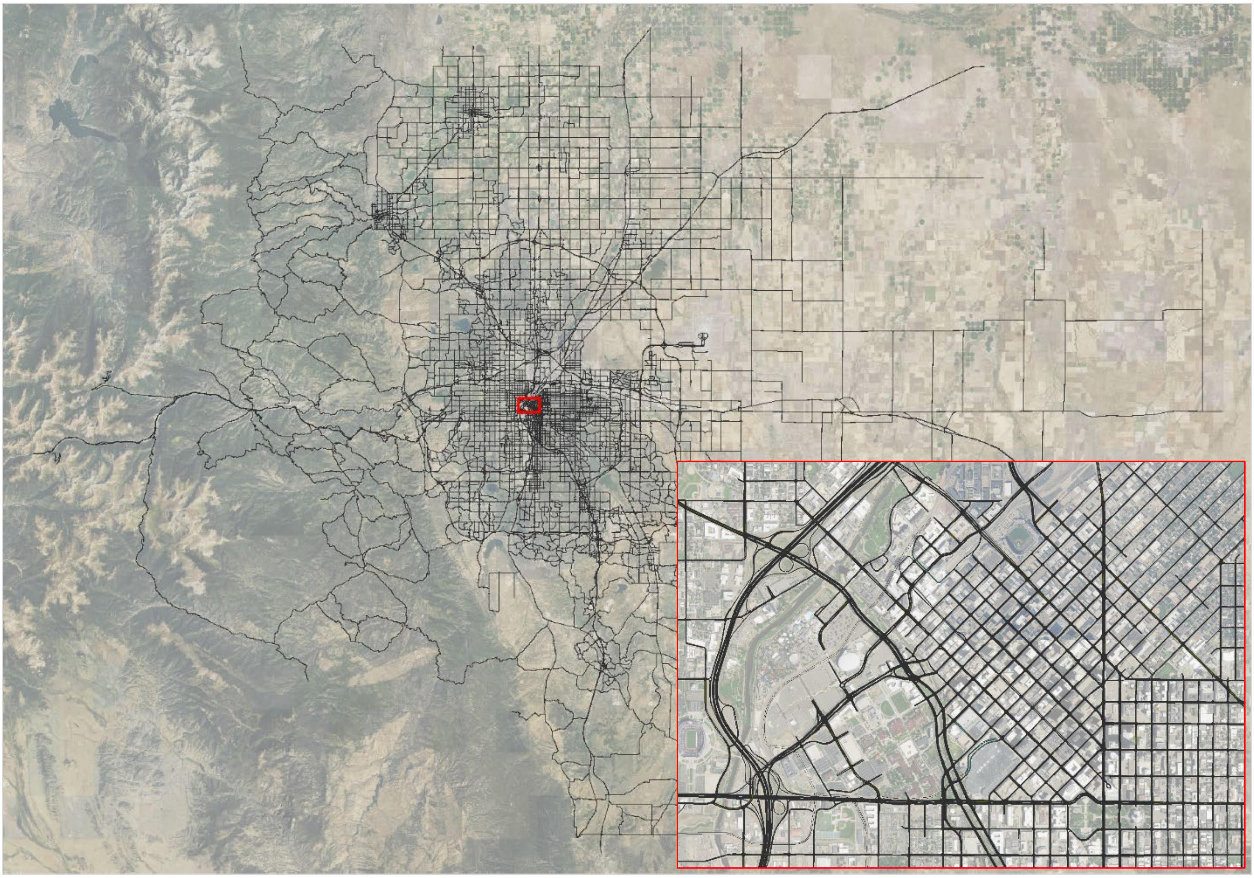

Figure 1. Lane-level map of the DRCOG regional planning network

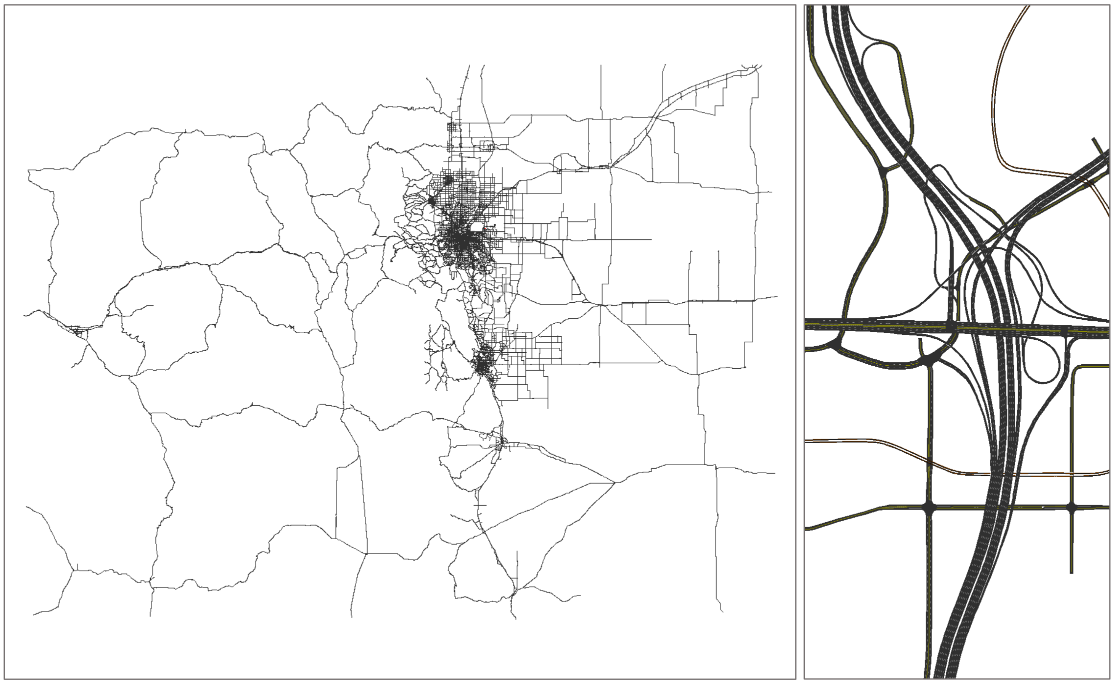

Figure 2. A lane-level map of the Colorado statewide planning model network

A second key data requirement is roadway attribute data describing roadway classification, signage, and traffic control.

Some attributes of the road network will be available from CDOT sources, including the ARNOLD system that underlies HPMS submittals. Other data sources within CDOT have been identified and cataloged as part of the effort to develop this implementation plan in order to develop recommendations regarding their use in developing DTA models in the state.

Key features of the highway network such as speed limits, message signs, ramp meters, toll gantries, etc. should also be coded in the proper locations. CDOT already maintains a comprehensive geographic signage inventory that will lend DTA model developers an advantage.

These data sources – ARNOLD and the roadway sign inventory – are just two examples of the traffic databases mentioned in the introduction of this document as a principal factor enabling wide-area DTA implementation.

A third critical data requirement for regional DTA is a shared zonal system with the regional planning model.

DTA models and planning models share some of the same input and resource requirements. Thus, efficiencies can be achieved if the DTA model is constructed in a way that makes it possible to exploit prior investment in the planning model. One of the most important ways to do this is to establish a common zonal representation or a zonal representation in the DTA model that can be easily related to that used in the planning model. Planners divide a metropolitan area into traffic analysis zones (TAZs) according to their demographics and land use characteristics, and these TAZs serve as the origins and destinations of trips in the model. However, DTA models might require a larger number of smaller zones to more reasonably model the loading points of traffic at origins and destinations. When the zonal representations of the two models can be shared or readily related to one another, they can, for example, more easily share important travel demand, travel cost, and related origin-destination (OD) data

For the foreseeable future, regional DTA models will invariably rely upon regional planning models to estimate the traffic volumes and patterns to be simulated, though those volumes and patterns may be further adjusted to improve validation with respect to field measurements. To be able to share traffic volume and pattern data between travel demand and DTA models, centroids of traffic analysis zones (TAZs) and centroid connectors between those centroids and the road network must be built up in the DTA model in a way that is compatible with the regional planning model. These connections between zones and streets may require augmentation and modification before they are suitable for the higher-fidelity simulation that sets DTA apart from traditional traffic assignment methods.

Perhaps the most challenging data requirement for any agency attempting DTA implementation is that of suitable traffic signal data.

Data describing the presence and nature of intersection controls are necessary for successful DTA implementation. Many DTA projects around the country attempt to cut this corner and make crude assumptions about traffic signal control and timing. However, accurate traffic signal information and reasonable treatment thereof in the model is critical to capturing performance on signalized arterials, especially when they stand in competition with congested freeways corridors.

Traffic signal data that is not readily available can be mined from other sources. For example, the locations of traffic signals can be captured from aerial imagery if they are not already maintained by CDOT or the MPOs. Some DTA tools will allow for traffic signal timing information to be imported from widely used traffic signal timing software products such as Synchro and from other electronic formats. Inevitably, signal timings will need to be approximated when they are missing from available sources.

In Denver, there are reportedly more than 3,500 signalized intersections within the DRCOG region, and more than 1,200 are operated and maintained by the City and County of Denver. DRCOG’s Traffic Signal System Improvement Program (TSSIP) has identified the benefits of moving these traffic signals under a centralized traffic signal system that supports remote access and upload and download of timing and coordination parameters. If strides are made by DRCOG and the City and County of Denver toward these technological advances over legacy traffic signal systems, then future DTA developments should tap into these systems to reduce the costs of developing the signal timing inputs that DTA models require. In the meantime, some DTA platforms are able to import signal timing data from the model files archived from signal timing studies overseen by DRCOG over the last 10 or more years. These signal timing studies were performed with Synchro, a widely used signal timing software that supports an open data format for sharing signal timing data.

Traffic counts are essential for developing, calibrating, and validating DTA and simulation models.

Some MPOs routinely collect and archive traffic counts so that they may be used for planning model validation. In simulation studies, a specialized data collection effort is often undertaken to support model calibration and validation. A well-maintained traffic count data inventory will be an important element to DTA development and maintenance long-term. In the short term, traffic counts used to develop the regional planning model and collected in prior traffic simulation studies in the region can be gathered and fused into a data set sufficient for initial DTA development.

Traffic count data collected for planning model development, however, may be limited to counts over long periods such as that spanning a peak hour or multiple-hour peak period. However, the longest useful time interval for modeling trip O-D patterns is probably 15 minutes. Accordingly, a sufficient number of 15-minute counts is required to build and calibrate a DTA model. Ideally, these would be classification counts distinguishing different types of vehicles, but typically that information is not available for most count locations.

Speed data are equally important to DTA model development so that it can be verified that the DTA model suibably captures key bottlenecks in the region.

Equally important to traffic count data are historical speed data that can be used to validate the model against observed congestion patterns. As is common practice with traffic simulation models, a DTA model is validated as a reliable tool for predicting project impacts when it is established that traffic simulated in the model matches, within reason, the location, timing, and duration of important bottlenecks. This kind of validation should be a minimum requirement of a DTA before it is adopted and deployed for decision-making. Ideally, the ability to validate a DTA for a subarea of a region should be undertaken before a DTA model for the entire region is developed.

Bottleneck location, timing, and duration can be readily observed from historical traffic speed data. Like traffic count data, it is preferable that speed data have a time resolution of 15 minutes or less. A variety of traffic data vendors such as HERE and INRIX sell historical speed data. CDOT, in fact, has purchased some of these data and hence has access to the kind of speed data that are important in DTA development.

There are a variety of sources for fine-grained traffic speed information that have not historically been available for use in modeling but can be very significant going forward. Derived from commercial data, but free for use by State DOTs and MPOs, the National Performance Management Research Data Set (NPMRDS) (4) provides estimated travel speeds by 5-minute interval for traffic message channel segments (TMCs) on a national road network for major roads. These data are available for every day of prior years and can be used to calibrate and validate traffic models. A summary description of the NPMRDS data can be found in Table 3.

Table 3. The National Performance Management Research Data Set in a Nutshell

Data Providers	INRIX, TomTom, HERE
Funded By	FHWA
Purpose	Support MAP-21 regulation and ongoing transportation system mobility performance measurement
Users	Federal, State, and regional agencies
Data Source	Probe vehicles
Metrics	Speed, travel time, and static AADT (2017)
Data Latency	One-month old
Lowest Temporal Resolution	5 minutes
Spatial Resolution	TMC level (about ½ mile to 1 mile in urban/suburban areas and 5-10 miles in rural areas)
Geographical Coverage	NHS
Modal Coverage	Truck and passenger car Data Format: CSV and ArcGIS shapefiles (road segment details)
Licensing Agreement	Required

Even more detailed data is provided under license from INRIX, the source for the NPMRDS. INRIX XD has even greater coverage than the NPMRDS data and is provided by roadway link across the country. Speed data is also available under license from HERE, both directly from HERE and from Caliper, who licenses HERE data for use with its software products.

CDOT Region 1 has access to another source of high-resolution speed data: the ramp metering system deployed on many of the freeways in the region and remote traffic microwave sensors (RTMS) also deployed throughout the region. These data are available at very high granularity, as little as one minute in the ramp metering data and 30 seconds in the RTMS data. CDOT's Applied Research and Innovation Branch (ARIB) has previously commissioned studies that call into question the availability and reliability of the RTMS data. If these data can be subjected to review and validation, then they could prove a valuable in-house source of data for model development.

6.3 POTENTIAL DATA RESOURCES FOR DTA DEVELOPMENT

In addition to a DTA model's baseline data requirements, there are other data resources that are not yet commonly used in the state of the practice or are emerging and carry great promise for DTA practice. These are described below, though this discussion is not exhaustive, and new data resources are likely to emerge in the years that follow this document's completion.

Origin-Destination (O-D) Data

DTA models and traffic simulation models make use of origin-destination trip tables specified by trip departure intervals**.** Reliable information of this type is not generally available from either public or private sources.

Many simulation projects begin with trip O-D data generated from a travel demand model. In our experience, the trip patterns, whether they come from a trip-based model or an activity-based model, do not match traffic counts very well and do not provide the 15-minute or finer granularity needed for dynamic modeling. In lieu of better sources of O-D data or improved resolution and accuracy of travel demand model trip tables, a dynamic origin-destination estimation (DODME) process is an essential step in every DTA model's development.

Location-Based Data

Location-based services (LBS) data is transportation data derived from cell phone apps that provide GPS traces**.** While LBS data do not come from a random sample of the population, they do provide observations for more than 1% of the traveling public. Aggregators obtain the data from cell phone carriers and license it to others who process it while maintaining traveler anonymity**.**

Commercial providers of processed LBS data include Streetlight, Cambridge Systematics, RSG, Replica, and Caliper. The offerings from these sources are varied but may include estimates of origin-destination patterns and vehicle trajectories. Figure 3 depicts the number of visit points – those data points representing the locations where trips ended – from LBS data in the Las Vegas, NV region. A concentration of points can be seen along the Strip, downtown, and in and around McCarran International Airport. The concentrations, timing, and sequences of these data points have much to say about the temporal activity patterns of trips in the region. If properly processed and applied, such data carries significant potential to support DTA modeling.

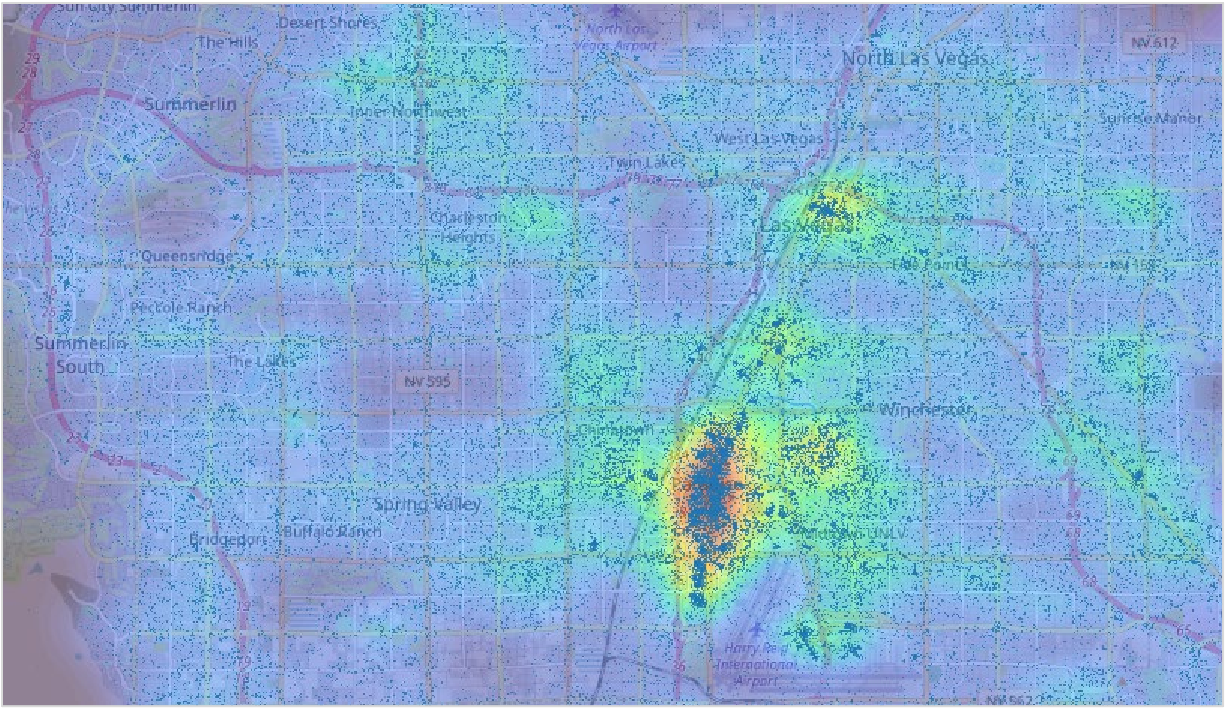

Figure 3. LBS visit points in the Las Vegas, NV metropolitan area

Specifically relevant to DTA is information on the time-dependent pattern of trips and access to actual vehicle trajectories. These data can greatly inform the DODME process. Since the LBS data come from a non-random sample of the population, the quality of the estimates necessarily depends on the expansion process. In our opinion, this is best accomplished with scaling to match locally collected traffic counts.

Connected Vehicle Data from Wejo

An additional source of data is that which is sent from vehicles to their manufacturer and packaged for sale by Wejo. Based upon an exploratory investigation of these data, we can say that a large amount of rather detailed positional data is provided for a reasonable sample of vehicles. Many more time points are provided for each vehicle trip so that trip routes are more properly discerned as are speeds and delay experienced.

The connected vehicle data do not come with unique vehicle IDs. Hence, the trip diaries cannot be simply observed, nor can vehicles be readily tracked over multiple days. Nevertheless, there appears to be considerable potential in utilizing these data in the DTA model development process.

Navigation Data

Navigation services and mobile apps provided by Google, Apple, HERE, Waze, Mapquest, and others give good quality *time-dependent* route recommendations upon request. Our experience with Google suggests that not only do they successfully provide good recommendations but that their predicted origin-to-destination travel times appear to be quite accurate.

While we don't have estimates of its influence, it is only logical to believe that at least a modest fraction of drivers follow the routes that are recommended by navigation services. Consequently, we believe that these routes can be used both in the construction and validation of a DTA model.

6.4 BASELINE DTA MODEL DEVELOPMENT

The core activity in a DTA model's implementation is the creation of a baseline DTA model and possibly several variants thereof. This could take the form of a very large model including all of the DRCOG region and the congested portions of corridors feeding into and out of the region from outside Denver. Alternatively, it could be done with one model for the core DRCOG region with separate models for one or more corridors.

The speed data described earlier in this report can be used to help identify the parts of the region that represent that "core" or that warrant inclusion in a DTA model developed for a corridor. For example, inspection of NPMRDS data for February 2022 shows the locations where significant delay is experienced on weekdays on the major roads of Colorado in the Denver area (Figure 4).

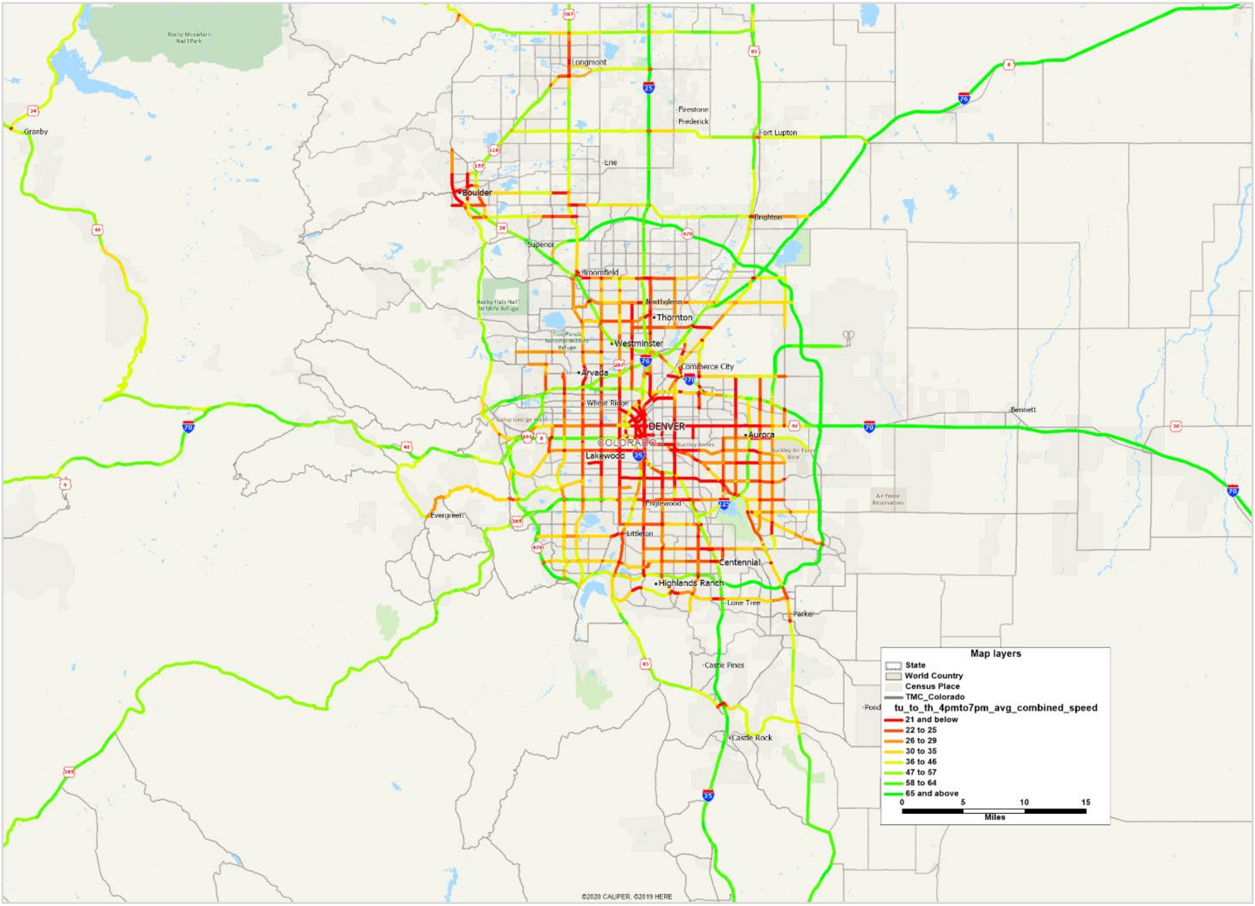

Figure 4. Areas of significant delay in the Denver region according to NPMRDS data

Similarly, the NPMRDS data reveal weekend travel delays on the I-70 Mountain Corridor. These delays are illustrated in map form and heat chart form for a Saturday westbound example in Figure 5 and Figure 6, respectively.

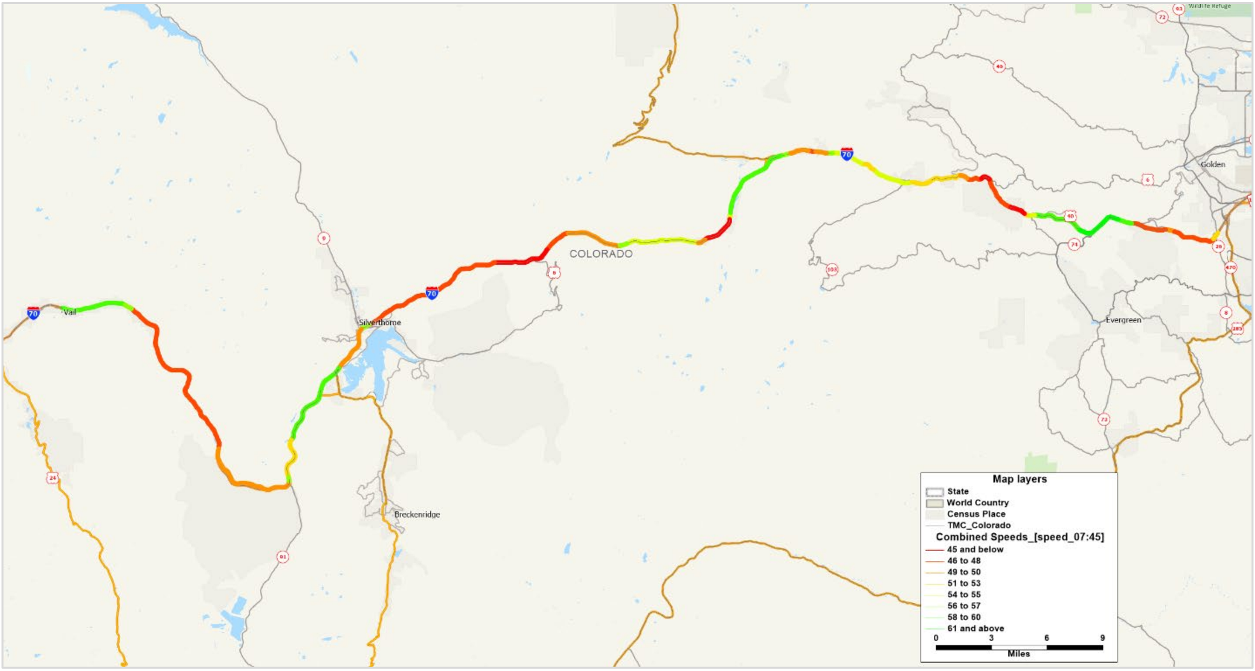

Figure 5. Winter weekend morning speeds on the I-70 Mountain Corridor according to NPMRDS data

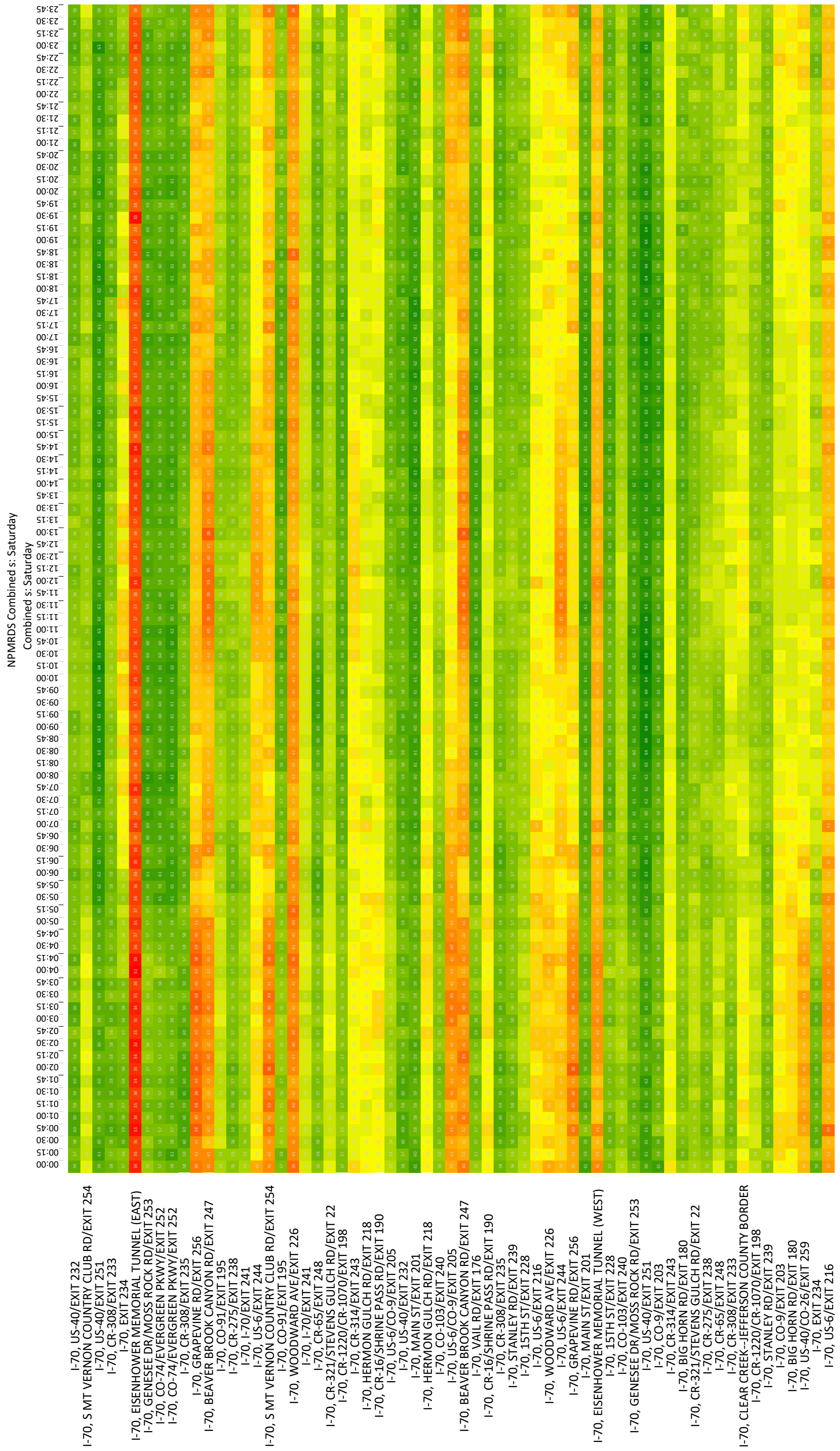

Figure 6. Heat chart depicting speeds by location and time interval on a Saturday on I-70

Initially, the focus in a DTA model's development would be on modeling the peak travel periods. A baseline DTA model would generally include a typical weekday scenario but could also be extended to have scenarios by season or to include a weekend model for either winter, summer, or both.

Our recommendation is to focus development on the Denver region and weekday travel because such a model would address a majority of the most pressing operations, planning, and policy issues facing CDOT and its stakeholders. The recommended coverage area might extend beyond the Denver region to include stretches of I-25 that are of high priority to CDOT, though compatibility with geographic boundaries of DRCOG's travel model would ease model development in many respects. If coverage beyond the geographic boundaries of DRCOG's model is desired, then the model might instead be constructed as a subarea CDOT's statewide travel model. Resolving all of the technical challenges in this model would provide a straightforward template for other regions, corridors, and MPOs that might ultimately have their own DTA models.

There are other options that may reduce the level of effort through, for example, narrowing the geographic area, but these would fall short of achieving the broad benefits that we have outlined. These other options should only be considered if the larger effort cannot be justified or funded.

Another alternative to building a model of an entire metropolitan region outright is to build the baseline model incrementally with parts of the model assembled from past and future simulation studies and perhaps small DTA studies that are conducted in the course of CDOT's and DRCOG's regular project planning and evaluation activities. We developed a list of recent simulation projects and examined a key one for I-25 in order to evaluate this alternative approach more formally.

A summary of what we found was documented in a separate memorandum provided to CDOT. Suffice it to say that simulation practice is too varied and too narrow to provide a sound basis for a wide-area DTA model. The incremental approach could work if the DTA developer did most of the simulation projects going forward, or if supplementary funds were provided so that the simulation projects could be re-implemented in a common framework. The former solution is not realistic, and the latter would be burdensome and costly.

Due to COVID's impact on travel patterns, we would recommend that a model be developed of either 2022 or 2023 traffic conditions. Whatever turns out to be the new normal will be the baseline going forward.

Core elements in base case model development include the following:

1. Data integration and synthesis to populate the model network with attributes and estimation of time-dependent O-D matrices.

   Once a DTA has been run and travel times and turning delays estimated, the model should be run to determine how well the simulated volumes and speeds on road segments in the study area match the counts and speeds in each interval. A Dynamic Origin-Destination Matrix Estimation (DODME) procedure is a critical step in the calibration process. The DODME procedure simulates the full peak period, computes a relative percent root mean square error (RMSE) across the complete set of count and speed locations for each interval, scores every trip on how well the counts and speeds are matched at the count and speed locations it passed during each interval in which it passed them, and performs one of four actions on trips that score most poorly: removal of the trip, cloning of the trip, shifting the trip departure one interval prior, or shifting the departure time one interval later. This process effectively calibrates demand to better match field-collected data by interval, thus preserving the time-varying characteristics of the model.

2. Import, creation, and needed timing or re-timing of traffic signals.

   In wide-area DTA models, signal timings may not be available for every signalized intersection. Where available, actual signal timings should be imported into the model. Software tools can be developed to automatically import traffic signal timing data from text or Excel files based on geographic coordinates, street names, and other available identifying data. Where existing signal timings are not available, they should be estimated based on demand and geometry. For example, if the intersection has a left-turn lane and the turn demand meets a user-specified threshold, a protected left turn phase should be included in the signal phasing. Signal timings should be estimated by time of day to appropriately address varying demand over the course of a day. When modeling future year scenarios, modification of green times is often appropriate to accommodate future year demand.

3. Calibration and validation of the model, which is accomplished through running numerous simulations and making refinements as needed.

   Calibration and validation of DTA models should aim at achieving (a) confidence that the DTA model and its underlying traffic flow model are capable of reflecting model year conditions, including regional traffic patterns and bottleneck locations, and (b) confirmation that the model is properly coded and that signal timing estimations and centroid connectivity are reasonable. Field data, such as counts, speeds, travel times, and bottleneck locations are the most commonly used data sets used for calibration and validation. An appropriate convergence criterion, such as one based on the percent root mean square error between travel times and delays of the current iteration and the previous iteration, should be selected to measure the effectiveness of the DTA.

   The calibration process is iterative, cycling back and forth between running DTAs and adjusting demand through the DODME process until no further improvement can be achieved in the overall relative RMSE. In each application of the DODME, numerous iterations are run, and the demand is adjusted in ways that are likely to improve the match with the counts. When the demand is judged to have changed significantly, the DTA is run again to update the expected travel times and turning delays and to achieve consistency between the changes in demand and congestion patterns on which route choices are based.

4. Sensitivity testing that verifies the model is appropriately sensitive to the policies and strategies CDOT or the MPOs might want to use the model to evaluate.

   After the DTA model is built, sensitivity tests should be run to test the model’s response to changes in model specifications. For example, demand can be scaled up or down, either globally or for certain critical links. Another option could be to add additional capacity, such as adding a lane, or changing the type of demand, such as percentage of automated vehicles or heavy vehicles. For tolled facilities, different pricing schemes can be tested.

Over time, project before-and-after data would be useful for refining the model further if warranted.

We recommend a development period of 18 to 24 months based upon our experience elsewhere. If needed, a usable model could probably be made available for some applications in a little over a year by sacrificing rigor and due diligence in calibration, validation, and sensitivity testing.

Once developed, the model will be available for supporting subarea DTA and simulation models. Windowing permits creating smaller and more targeted models that would be used for project work by consultants and in-house analysts.

6.5 MODEL DEPLOYMENT, MAINTENANCE, AND USER SUPPORT

The availability of a baseline DTA model is expected to reduce the costs and improve the quality of future traffic analysis work. For those benefits to be realized, a model deployment, maintenance, and user support program will be needed. The following are important model maintenance activities that are recommended.

Use and Update of the DTA Model in Traffic Analysis Studies

Deployment of the DTA model entails its dissemination for use by consultants and government agency staff. The most current version of the model and possibly other prior versions should be available for download for agency staff and for approved consultants.

As the DTA model is used for various studies over time, those studies should double as opportunities to improve the baseline model. This practice should be part of a continuing model maintenance effort.

Given that not all simulation or traffic analysis work may be performed in the same platform as the DTA, there should also be provision for data conversion to the DTA platform. This could be the case both for complex evaluations of corridors and for models as simple as intersection analyses performed with traffic signal timing software like Synchro.

Also, and perhaps most importantly, further and more refined calibration of the baseline model should be part of its normal use. Detailed examination of study calibration efforts and results will provide the basis for improving estimates of dynamic O-D matrices and possibly other aspects of the baseline model.

Update of the DTA Model for Technological Currency and Relevance

Like regional planning models, a regional DTA model must be maintained continually in order for it to evolve with ever-shifting travel behaviors and traffic flow patterns that vary with societal and economic factors, transportation supply, and technological change.

Labor force participation, work from home, and e-commerce are among the societal dynamics that influence peak period traffic flows. Similarly, mode choice is not a static or constant phenomenon as attitudes toward walking, cycling, and other modes shift and demographics change.

Transportation supply is similarly changing with introduction of new facilities, changing characteristics of vehicle fleets, and transportation system management activities such as improved ramp metering and dynamic pricing.

The DTA must also simulate new transportation options and technologies in order to be useful in planning for them. Practitioner knowledge of these options and technologies also evolves with time. Hence, a key activity of a model maintenance program is to progress the tool to be relevant in analyzing the impacts of new technologies as our understanding of them improves.

CAV modeling is a good example of the need for advancing our modeling tools to meet technological change. The increasing deployment of various vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) technologies will evolve with changes in onboard vehicle equipment and in the surveillance and control infrastructure that will communicate with vehicles. As standards emerge, it will be possible to incorporate more realistic treatments of the movements of CAVs.

Performance of Before-and-After Studies

Use of the DTA model should be tracked and documented, and significant modeling efforts should be archived. This is commonly done for travel demand models, but model preservation and maintenance for DTA should be different. Typically, travel demand forecasts are made for long-term horizons of 20 to 30 years, and thus there is never really a good opportunity to revise a model based upon its forecasting performance.

In contrast, many but not all uses of the DTA will have a shorter-term focus. As a result, it should be possible to observe concurrences and disparities between model predictions and real-world observations post-implementation (e.g., after a facility has been constructed and opened to the public). Thus, it will be possible to evaluate some of the forecasting performance of the DTA and to revise it based upon insights obtained.

Before-and-after analyses will be particularly valuable for toll facilities. Once the facility is opened, there will be an opportunity to evaluate and refine the toll price elasticities for various facilities and dynamic tolling policies. This will not only potentially enhance revenues, but it will be an opportunity to improve the baseline model.

Before-and-after studies are the gold standard and principal method of in-depth validation of transportation models and provide the basis for correcting and refining forecasting models. Over time, project impacts that were forecasted pre-implementation can and should be compared with observations of actual impacts. This should include an investigation of the accuracy of assumptions about inputs in addition to a simple comparison of forecasts and conclusions.

Model Recalibration and Validation

The DTA model should be recalibrated and validated either every several years or at irregular intervals based on need. Each recalibration and validation effort presents the opportunity to meet the following key objectives:

1. Keep pace with trends in demographics and technological change.
2. Incorporate new data that may become available and that may be integrated with the model.
3. Keep the model current with the latest software versions, which may address data errors and software bugs but that may also include model running time reductions and incorporate newer and better traveler and driver behavioral modeling methods.

Model User Support

Ongoing user support should be considered an essential activity that is a necessary part of the DTA program. A user support system would allow the agency responsible for the DTA model to:

1. Make the appropriate versions of the model available to users
2. Answer questions about how to run the model
3. Provide some advice in how to apply the model to specific projects.

If the agency has the staff and resources, then the user support services may also extend to encompass peer review and quality assurance services for key projects.

User support could be provided by agency staff or by a contractor or a combination thereof. In order for the benefits of a DTA resource to be fully realized, user support will need to be made available on a timely basis because rapid technical support is often required to keep projects on schedule and within budget. Effective application of DTA is often a cooperative and collaborative enterprise that hinges on the ability to draw upon the experiences of other, perhaps more experienced DTA model developers and users, particularly those experienced performing projects in the state.

6.6 ANCILLARY, SUPPORTING PROGRAM ACTIVITIES

As with any activity that entails professional community engagement and involvement, a DTA modeling program should be supplemented with training and technical guidance. The goal of these efforts is to equip public and private sector staff to make effective use of traffic simulation and DTA models.

Training

Given the target audience of consultants working in Colorado, targeted training for DTA modeling should be conducted. Consultants need to understand how to modify the DTA model in order to apply it in project work. The training should include not only basic concepts and model operation, but good practices in calibration, validation, and interpretation of results.

Technical Guidance for DTA and Simulation

Clear written technical guidance for applying DTA and simulation will be very helpful in supporting the smooth application of DTA models and progressing the DTA program in the future. Several states have developed simulation guidance that is helpful in standardizing and improving simulation practices. For example, the Ohio DOT has developed the Ohio Analysis and Traffic Simulation (OATS) manual that standardizes their traffic analysis process both for capacity and simulation studies. The same could be done for DTA application in Colorado. If CDOT embarks upon a DTA effort, one of the deliverables can be technical guidance for how DTA models should be applied.

User Group Support

A model user group would be a useful adjunct to the DTA program, providing a mechanism for information dissemination and obtaining feedback from users. The user group might conduct virtual meetings every few months to share information and experiences. The Ohio DOT, for example, holds an OATS user group meeting twice a year to share information about experiences applying the OATS manual. A support site provides access to the manual, standard documents and forms, and sign-up to join the user group:

https://www.transportation.ohio.gov/working/engineering/roadway/manuals-standards/oats-support/oats-support

7.0 MANAGEMENT OF A DTA CAPABILITY: ROLES AND RESPONSIBILITIES

In this section, we make suggestions about program roles and responsibilities. These are offered up for CDOT consideration and could take many alternative forms based on organizational factors of which we have no knowledge.

CDOT is the appropriate steward and overseer of DTA modeling efforts. Either CDOT's TSM&O or the Information and modeling group would be the logical home for management of this effort. Alternatively, it could be a joint or broader collaborative effort. For instance, the actual implementation of the core DTA model capability may potentially be implemented by a contractor subject to the direction of a CDOT program manager.

CDOT would have the responsibility for procurement and management of the contract effort. CDOT will need a DTA program manager and will need to cover several management responsibilities in addition to providing direction to the implementation contractor and performing administrative contracting and technical oversight tasks. This need not be a full-time role, but, in our experience, it would be helpful if the program manager is well-regarded by upper management, is a champion of the program, and is articulate in describing its benefits and successes.

A single CDOT program manager is recommended with a possible Deputy Program Manager to help ensure continuity of management. A CDOT DTA advisory committee or steering committee would coordinate Departmental efforts at headquarters and with the Regions. This advisory committee could include MPO representatives at CDOT's discretion. Optionally, a broader technical advisory group might include consultants, academics, and other relevant and qualified parties.

In some of our earlier discussions, we identified the Information Branch as a good home for a DTA effort. In our experience, successful DTA models require a strong understanding of travel demand modeling concepts in addition to models of traffic flow. CDOT is fortunate in having staff that are knowledgeable in advanced modeling and the concepts involved with DTA. There are also key synergies in integrating DTA with ongoing information management systems and activities.

The main consumers of DTA model application outputs will be the traffic engineers at CDOT headquarters and in the Regions, and this group is the other logical lead for the DTA effort. Housing the DTA program within TSM&O at CDOT will perhaps be strategic in terms of fully realizing its potential benefits.

CTIO may have the greatest direct financial stake in application of a DTA models both for toll revenue forecasting and evaluating future investments. As such, CTIO's interests should be well-represented in DTA program efforts. We suggest that CTIO be treated as a most influential client of a DTA program rather than as being the lead of the effort.

An alternative to designating a single CDOT branch or project manager is to form a steering committee to oversee DTA development, maintenance, and application. This could also be a good idea even if it is not an alternative but a supplement to having a single project manager.

8.0 IMPLEMENTATION TEAM

Very few transportation consultants have actually developed DTA models in a professional setting because it is emerging rather than established practice. Consequently, an expert consultant team with considerable prior experience with high-fidelity DTA models will be needed to develop the model and provide the initial round of technical support to users.

Irrespective of which organization in CDOT has the lead responsibility for the DTA program, it will be important to have internal coordination with various groups whose work objectives and work products are directly related to development and use of a DTA model. At its option, some CDOT staff could participate in the project work both during baseline model development and thereafter. Overall, responsive cooperation and astute oversight by CDOT staff will help ensure the best product.

9.0 BARRIERS TO DTA SUCCESS AND THEIR MITIGATION

Traditionally, there have been a number of barriers to successful development and deployment of DTA models. While some of these have been traceable to inadequate software, there are definitely challenges that are inherent in any DTA effort. Understanding these challenges is helpful in addressing them and in formulating a program destined for success.

9.1 OVER-RELIANCE ON TRAVEL DEMAND MODEL (TDM) ASSUMPTIONS AND OUTPUTS

Used for different purposes and held to typically much lower validation standards, travel demand models do not provide good enough estimates of trips to support realistic DTA models. While it is possible that this might change in the future when the DTA models can inform the travel demand models, one must assume that a DTA model will produce a different portrait of system utilization than the travel demand models. Virtually all travel demand model outputs will need to be modified to be suitable for use in a DTA. Often, there will be unrealistic levels of traffic in excess of available capacity. The solution is not to constrain the DTA to be consistent with the TDM but rather to try to learn from experiences developing and applying DTA where and how the travel demand model might be improved.

9.2 INSUFFICIENT FIDELITY TO SUPPORT TRAFFIC OPERATIONS ANALYSIS

Some prior DTA failures have been attributed to unrealistic traffic models, especially those that have been simplified in terms of geometry, effects of capacity, and signal operations. In our experience, many mesoscopic models are still oversimplified and will not be properly responsive to modeling congestion and route choice. Care must be exercised to use microscopic simulation for DTA when it is necessary to represent and reflect the behaviors of interest.

9.3 DATA AVAILABILITY

In the past, obtaining the data needed for an adequate simulation model was challenging and sometimes either cost- and/or geographic scale-prohibitive. If field surveys and aerial photography were required, data collection would often be limited to a narrow area or a small number of locations. Improvements in data availability do mitigate this situation, but it can still be challenging to obtain sufficient O-D data by time period. We believe that some of the new data sources described earlier in this document may be very helpful in addressing these data needs.

9.4 INSUFFICIENT CALIBRATION, AND VALIDATION

A particularly challenging aspect of DTA model development is achieving sufficient validation to volumes and speeds. As described previously, a core technical challenge is estimating dynamic origin-destination matrices from counts and speeds. There is not a single, definitive mathematical procedure for accomplishing this task. Rather, a mixture of human interaction and algorithmic processing has been shown, given enough time, to produce reasonable results. Allowing sufficient calendar time for calibration and validation is the single best way to mitigate the problem.

9.5 COMPUTATIONAL BURDEN AND LONG RUN TIMES

Simulation models are computationally intensive when compared to other analysis tools, and multiple model runs are required. A DTA requires even more computation in order to achieve model convergence and internal consistency.

Fortunately, modestly priced and widely available computers get faster every year, reducing the time needed to compute DTA models. Software advances also contribute to reduced run times.

Because long run times are often unacceptable to users and inhibit broader acceptance of DTA, we implemented an uncalibrated prototype DTA for the DRCOG region to validate our proposed concepts, demonstrate their feasibility, and provide some benchmarks for what could be expected in terms of run times and computer requirements.

A mesoscopic DTA model with highly detailed lane-level geometry capable of supporting microsimulation was created in TransModeler, and O-D trip matrices produced by the DRCOG activity-based model FOCUS for the AM peak period from 6:00-9:00 am were simulated. In the three-hour peak period, the DRCOG model predicts demand in one-hour periods (e.g., 6:00-7:00 am, 7:00-8:00 am, and 8:00-9:00 am) totaling about 1.9 million auto and truck trips. Only modest adjustments were made to further subdivide the hourly volumes into departure intervals of 15 minutes in length. This finer temporal distribution (Figure 7) was asserted while preserving the hourly totals predicted by the DRCOG model but could be derived from traffic counts or other traffic data.

DTAs work by iteratively simulating the full simulation period and updating route choices of trips. Run times in our experiments with the prototype varied with the degree of congestion between 11 and 18 minutes on a modern, reasonably powerful desktop PC, suggesting total model run times of between 10-15 hours if 50 iterations, the higher end of the number that may be needed, are performed. However, more recent experience suggests fewer than 50 iterations are needed when the DTA is warm-started, and run times may be as much as halved when a predetermined set of paths is initially derived and the DTA merely chooses a route for each trip from the set. These results make it clear that a regional DTA even for Denver can have acceptable run times.

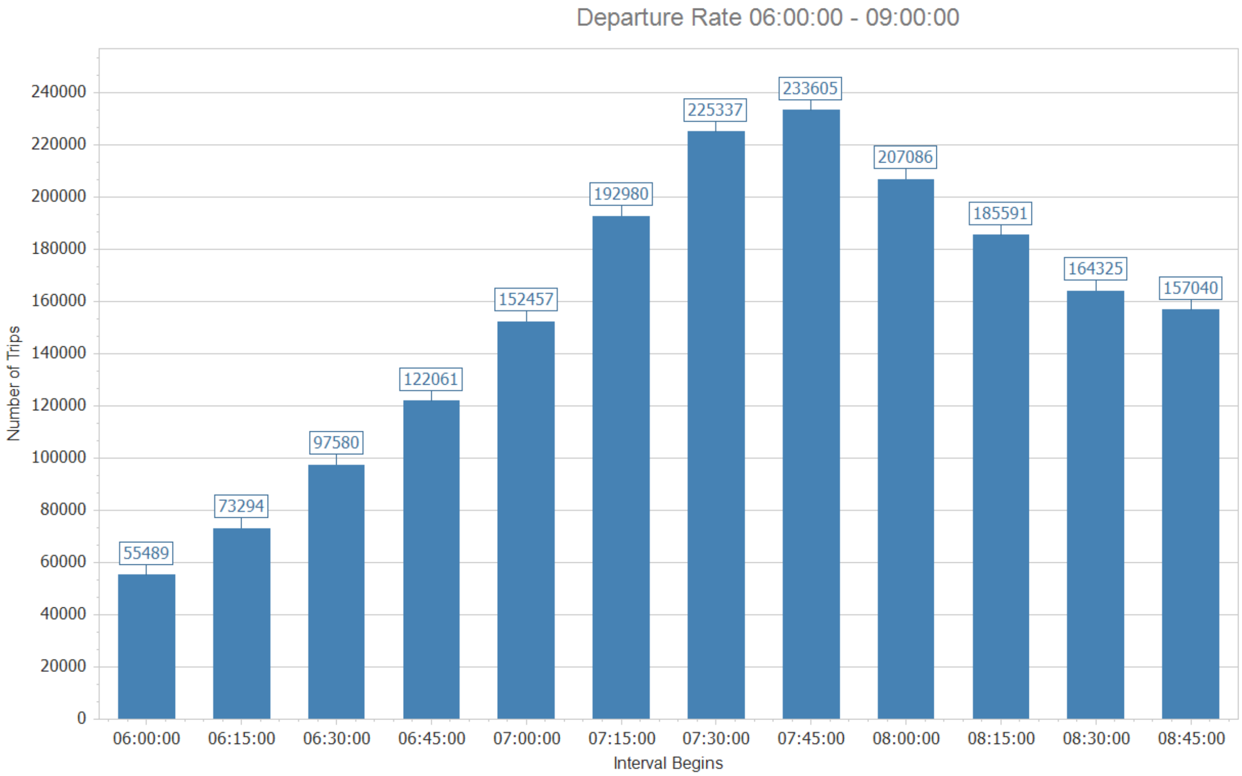

Figure 7. Assumed temporal distribution of AM trips in the prototype DTA for the DRCOG region

9.6 COMPETITION FROM OTHER TRAFFIC ANALYSIS TOOLS

As fairly elaborate efforts, DTA and simulation models face competition from other simpler traffic analysis tools. It is not uncommon for simpler tools to be preferred even when they are ill-suited for the applications for which they are used. A good example is the use of Synchro, a widely used tool for signal timing and optimization, for analysis of freeway facilities, for which Synchro was not originally nor well designed. Even for arterial intersections, Synchro is over-simplified. See Appendix A for a relevant discussion.

It is important to distinguish between the recommended style of DTA and other traffic analysis tools and methods. This is because the motivation for DTA is derived in part from the limitations of the other tools that are commonly used by planners and engineers. The DTA model will typically have a broader geographic scope, greater realism in modeling traffic operations, and a greater sensitivity to all dynamic traffic management strategies.

An important mitigating factor is demonstrating how the DTA can be used to support simpler traffic analysis through windowing of intersections and freeway facilities and how single-shot simulations and application of Highway Capacity Manual (HCM) methods can be made while retaining the greater accuracy and sensitivity from the DTA.

10.0 FUNDING REQUIREMENTS

Based upon experiences in DTA development elsewhere, we would recommend a budget of $800,000 to $1.2 million dollars and a project duration of 1.5 to 2 years. The lower-end budget level would be appropriate for just the core of the Denver region and the higher level would be appropriate if longer or additional corridors are included.

With annual funding of 15% or between $120,00 and $180,000, subsequent development would be sufficient for the ongoing maintenance and support activities that we described previously.

11.0 POTENTIAL FUNDING SOURCES

Funding for DTA need not be especially onerous if it carefully integrated into the work programs of various organizations. We suspect that it could be completely funded by using the tool in place of others that would normally be used in studies. However, this suspicion requires confirmation from CDOT.

CTIO alone spends a considerable amount on toll and revenue studies that could be both improved and made more cost-effective if a suitable baseline model was available. Given CTIO's toll setting responsibilities, a DTA could be justified as a revenue management tool as well.

A DTA program of the type outlined here would be considered highly innovative and as such would likely qualify for outside funding from FHWA. For example, it might be funded under the Accelerated Innovation Deployment (AID) Demonstration Program.

Others at CDOT and FHWA should be consulted as to grant opportunities that may be available.

12.0 PROJECT TIMELINE

A typical 18-month timeline to develop, calibrate, and validate a regional mesoscopic DTA model is depicted in Figure 8. Timelines might be longer depending on data availability, particularly that relating to signal timing information, and for microscopic models. If signal timing data cannot be obtained and must be estimated or optimized, inputs that require additional testing and review before they are refined enough for simulation. Microsimulation-based DTA models will generally be more sensitive to the quality of all of the model's various inputs, including centroid connectivity, geometry, and signal timings, and hence also generally require additional time to develop, calibrate, and validate.

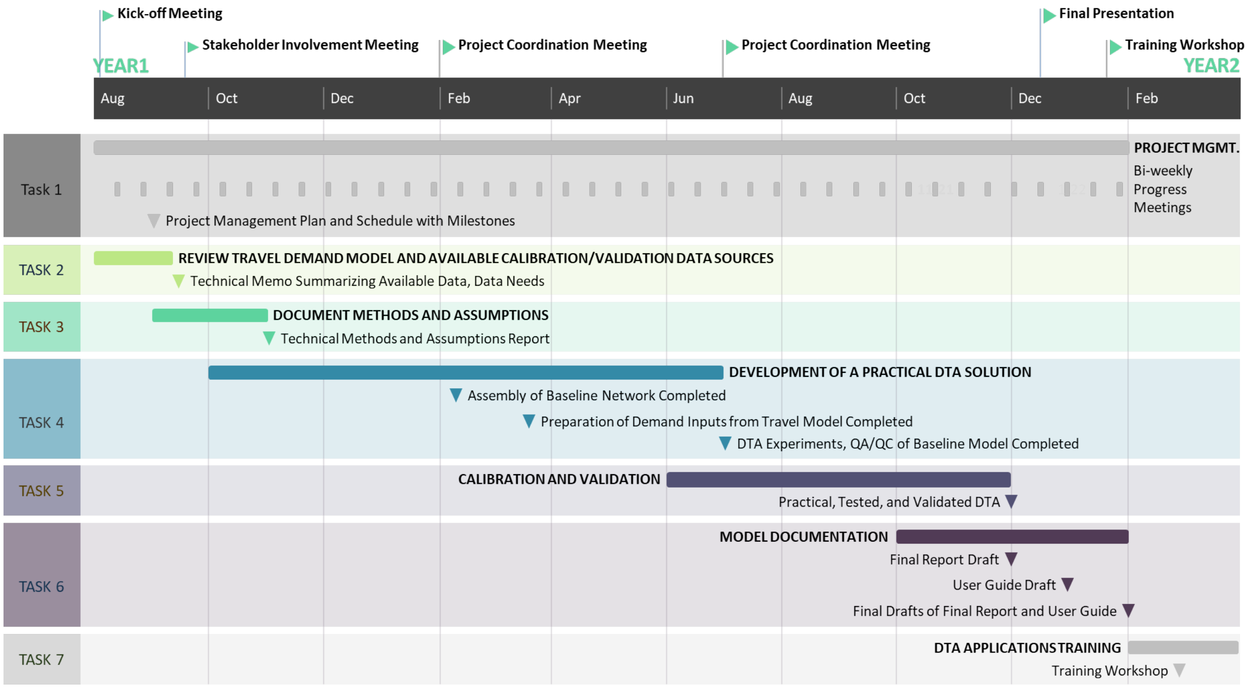

Figure 8. A Typical Timeline for Development of a Regional DTA Model

A DTA development effort will typically include documentation and training tasks so that knowledge about the model’s construction, inputs, and data requirements can be transferred to the agency assuming ownership and maintenance of the model.

13.0 CONCLUSION

The motivation for regional DTA models is both straightforward and commonsensical. The time-varying nature of traffic is one of its most obvious characteristics, yet it is often ignored in traffic forecasting. Traditional and even innovative travel demand models fail to treat varying network characteristics in a realistic manner working with multi-hour analysis periods. DTA models seek to provide a greater degree of realism and accuracy by modeling traffic flows in short time intervals.

The increased temporal fidelity and operational realism, while largely an advantage, have meant computation time and model complexity that compound as the size of the region increases. However, a regional DTA has never been more feasible and practical even for very large MPOs thanks to advances in modeling software and computer performance. The vision for a DTA for the Denver Metro Region and smaller MPOs presented in this report would have sufficient temporal resolution to support traffic engineering assessments of system impacts in a better fashion than can be achieved with isolated traffic analyses.

Whereas traffic simulation, without any modeling of route choice, has been the traditional tool of traffic engineers, traffic assignment has largely been the tool of transportation planners for estimating project impacts. These assignments, however, are macroscopic in their treatment of traffic flow and as such have even less of the detail and operational sensitivity than mesoscopic models.

DTA represents an intersection of engineering and planning methods and is still gaining ground among practitioners in Colorado and across the United States. If more accurate simulation and better decision-making are the goal, then the future of project evaluation and alternatives analysis must embrace DTA. Conventional microsimulation methods and practice are simply not suited for the projects of today, particularly those that involve dynamic tolling or impacts that reverberate across parallel routes and adjacent facilities or that will affect the route choices that drivers will make.

To take up DTA and to realize its advantages will require a process of training and education as well as the costs that come inevitably part of the adoption of newer and better methods. However, the costs of simulating a proposed roadway project before it is built are and will be dwarfed by the capital cost of implementing the project, not to mention the cost of making a poor decision in the absence of operational insights that DTA can provide. The more accurate the analysis, the better the design decisions will be and the greater the return on investment. A well-executed DTA will provide better, more accurate models than simulation alone.

Improving project evaluation and prioritization through DTA will hinge not only on improved technical methods and modeling fidelity but also on buy-in from CDOT and its planning and engineering partners. An implementation plan that assimilates the views of diverse stakeholders will be best positioned to address analysis priorities. The authors of this report have endeavored to incorporate those views into all aspects of the preparation of this document with the hope that it will help spur the emergence of new modeling tools that will provide better answers and significantly lower analysis costs in the future.

14.0 REFERENCES

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15.0 APPENDIX A: DETERMINISTIC TOOL LIMITATIONS

Traffic operations analysis tools are grouped into two types: deterministic and stochastic. Deterministic tools are not subject to randomness, and each application of the tool, given the same inputs, will produce the same outcome. The most widely used deterministic methods for traffic operations are those documented in the *Highway Capacity Manual (HCM)*. The most commonly used software tools that implement the HCM methods are Synchro, developed by TrafficWare, and the Highway Capacity Software (HCS), developed by the McTrans Center at the University of Florida. FREEVAL, the computational engine used in the development of the HCM Freeway Facilities method, is also used for project evaluations in North Carolina and in a few other locations.

HCM methods, and thus the tools that implement them, are limited in their ability to deal with certain situations, including:

- Oversaturation
- Queue spillback or overflow
- Freeway-arterial junctions (the new HCM 7th Edition includes a deterministic method to evaluate these junctions; the implementation of the method in HCS is expected sometime in 2022)

15.1 OVERSATURATION

Oversaturated traffic conditions occur when demand exceeds capacity (i.e., demand-to-capacity, or D/C, is greater than 1.0). Historically, the HCM Signalized Intersection method could not accurately estimate delay and queue lengths when D/C > 1.0. The method was improved with an update to the HCM in 1997 to allow the method to better incorporate additional delay associated with unserved demand for the analysis period. Instead of one signal analysis period (typically 15 minutes or one hour), an analysis is conducted for several successive 15-minute intervals that comprise the overall peak period. For each incremental 15-minute period, the unserved demand for a previous 15-minute is added to the demand for the next period. The analysis is continued until a 15-minute period is reached where the total demand is less than the capacity. The HCM advises the use of a multi-period analysis when demand exceeds capacity.

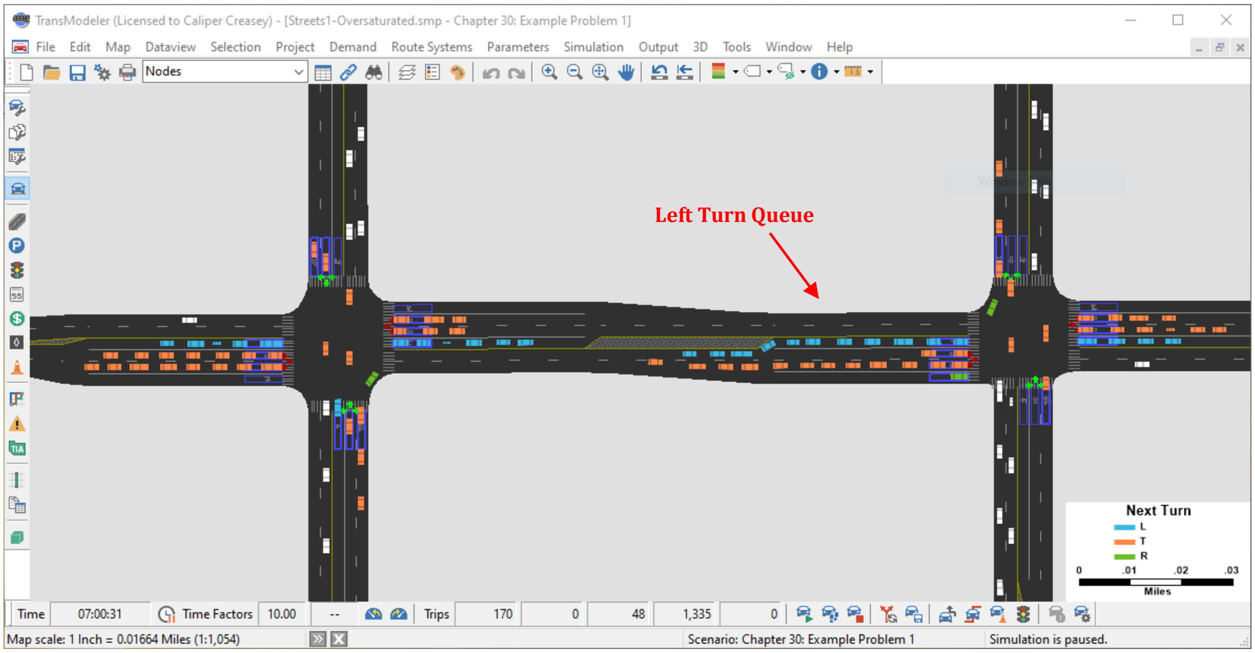
Regarding software tools, the HCS is capable of performing a multi-period analysis for several of the methods. The software does not do this automatically; it is up to the user to select the multi-period option and enter the data correctly. Synchro does not perform multi-period analysis, although it purports to implement HCM methods. While Synchro does allow the user to enter a value for unserved demand, it is extremely difficult to estimate this volume accurately for a 60-minute period, and the user is left to come up with the method to produce such an estimate. The HCS computes unserved demand automatically when a multi-period analysis is employed. An article by Creasey and Sampson (1) illustrates, when conditions are oversaturated, how failure to apply a multi-period analysis significantly underestimates delay at an intersection.

15.2 QUEUE SPILLBACK

Queue spillback is a frequent by-product of oversaturation, although it can also happen in certain situations when traffic conditions are under-saturated. Queue spillback on urban streets commonly happens in one of two ways:

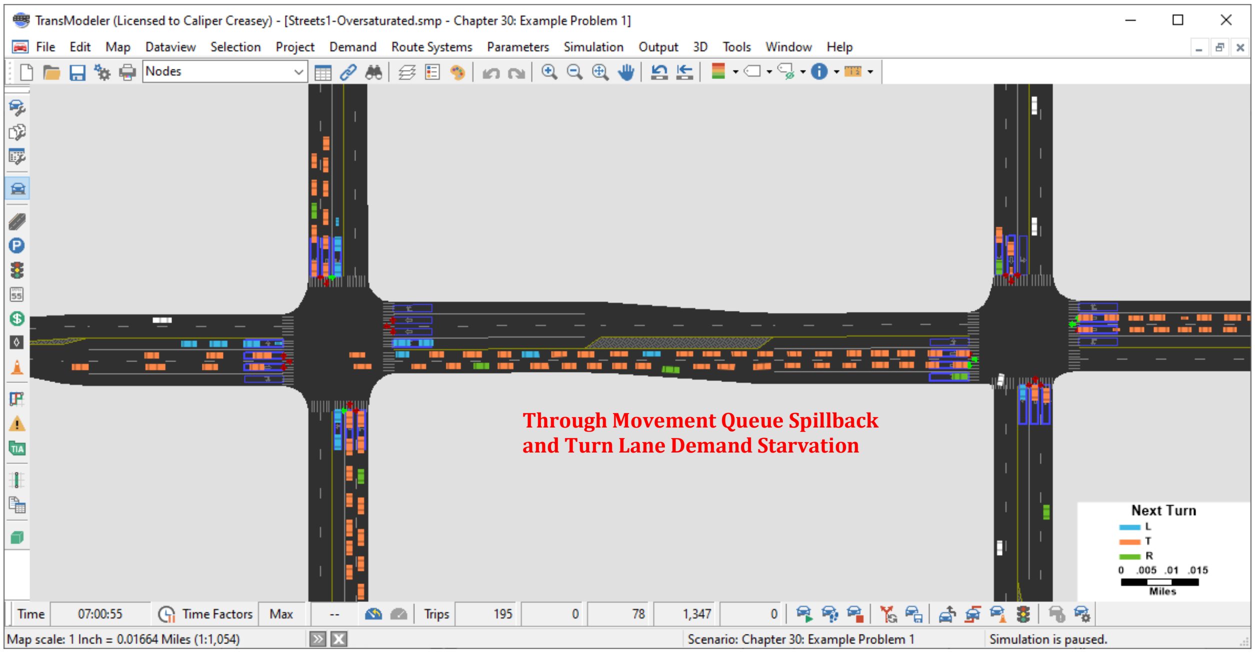
- A turn bay or pocket is overloaded, and the queue spills back into adjacent lanes, impeding through traffic flow and starving utilization of adjacent lanes (Figure 9); and
- Traffic queues at one intersection back up into a nearby upstream intersection, impeding flow at that upstream intersection. In this scenario, demand starvation also is common, where turning vehicles at the

downstream intersection are not able to reach the turn bays because of the heavy backups with the through movements (Figure 10).



Left Turn Queue

Figure 9. Queue spillback leading to demand starvation in microsimulation



Through Movement Queue Spillback
and Turn Lane Demand Starvation

Figure 10. Queue spillback between adjacent intersections in microsimulation

Deterministic tools such as Synchro and HCS are extremely limited in their ability to account for queue spillback due to limitations in the HCM methods they implement. Essentially, these tools can only notify the user when the spillback conditions exist, but they do not adjust those flows that are impeded by the spillback conditions. Corresponding performance measures also are incorrect when these impacts are not included.

15.3 FREEWAY-ARTERIAL JUNCTIONS

Service interchanges provide the interface between freeways and arterials, but deterministic methods to evaluate freeways, arterials, and the ramps that join them have been isolated models until only recently. The new HCM 7th Edition, to be published in early 2022, will include a network analysis method to evaluate these facilities collectively, as a system. It is believed that a subsequent release of HCS will include a corresponding software implementation as well. However, based on the HCS computational engine that was developed to support the research that produced this method, it is anticipated that the software will only provide a link between HCS freeway facilities and arterial analysis files. In other words, the user will have to prepare separate HCS freeway facilities and arterial analysis inputs first. There will be no unified user interface to create the files and perform this analysis all in one place.

It is unknown whether Synchro will include this method in a subsequent version of the software. Currently, Synchro is incapable of performing any freeway-related analysis, although users commonly model a service interchange ramp approach as an urban street. On most ramps, vehicles are continuously decelerating along the ramp length until the stop bar at the end is reached. This is not necessarily the case for most urban streets; even minor street approaches have more constant, albeit slower, approach speeds. Using the software to model a ramp as an intersection approach leg is rough approximation of the operation, one that is better and more accurately treated through other microsimulation tools.

Synchro is not able to evaluate any type of uninterrupted flow facility: freeways, multilane highways, or two-lane highways. Whereas the HCS includes individual modules that implement HCM methods for each of these facility types, Synchro's primary focus is on urban street facilities, including signalized and unsignalized intersections, along with roundabouts. While uninterrupted facilities make up a significant portion of the total roadway system in most states (especially two-lane roads), Synchro does not model them.

15.4 MICROSIMULATION TOOLS AS AN ALTERNATIVE

Microsimulation tools are stochastic in that they incorporate random variables to represent model attributes that are not known with certainty. Different random sequences will produce different results; therefore, microsimulation models are typically run multiple times in order to form a range of expected traffic conditions given the variation that is seen day-to-day. Widely used commercial traffic simulation tools include TransModeler, Vissim, and Aimsun.

By their inherent nature, a strength of microsimulation tools is that they are able to evaluate those conditions that are limitations of the methods in the HCM. The HCM even dedicates two chapters to discussing the relationship between the HCM and alternative tools (i.e., simulation) and provides guidance on when alternative tools should be used in lieu of the deterministic methods, especially for those situations just described.

15.5 ABOUT APPENDIX A

This appendix is intended to provide a perspective on deterministic traffic analysis tools, with which readers of this report may be more familiar, and their limitations relative to traffic simulation and DTA tools. It is authored by Thomas Creasey, PE, Ph.D. of Caliper Corporation. Dr. Creasey is the former chair of the Transportation Research Board's Highway Capacity and Quality of Service committee, which oversees the Highway Capacity Manual (HCM).