TravelWorks Integrated Models

Final Report

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13. ABSTRACT (Maximum 200 words)

SHRP2 provided implementation assistance to four pilots and one lead adopter to explore advanced integrated travel models. The four C10 pilots aimed to evaluate integrated activity-based travel demand models (ABM) and dynamic traffic assignment (DTA) models. These models have a fine-grained time and space resolution, and thus can be used to address pricing, management, and operations strategies for both highways and transit. The C04 lead adopter incorporated reliability and pricing into an existing planning model. This report summarizes the activities and results for the four C10 projects.

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Executive Summary

SHRP2 provided implementation assistance to four pilots and one lead adopter to explore advanced integrated travel models. The four C10 pilots aimed to evaluate integrated activity-based travel demand models (ABM) and dynamic traffic assignment (DTA) models. Compared to current practice models, these offer more detailed representation of system dynamics (scheduling, queuing, traffic control), and thus can be used to address pricing, management, and operations strategies for both highways and transit. The C04 lead adopter incorporated reliability and pricing into an existing planning model.

Implementation assistance was provided for the following projects:

- Two pilot projects, with Atlanta Regional Commission (ARC) and Ohio State Department of Transportation (ODOT), to integrate their CT-RAMP ABM with the DynusT DTA in a highway setting
- A pilot project, with Maryland State Highway Administration and Baltimore Metropolitan Council (BMC) to integrate the University of Maryland agent-based model (AgBM) with dynamic traffic assignment (DTALite), as well as a BMC's activity-based model (INSITE) with dynamic traffic assignment
- A pilot project, with Metropolitan Transportation Commission (MTC), San Francisco County Transportation Authority (SFCTA), and Puget Sound Regional Council (PSRC), to implement the Fast-Trips dynamic transit passenger assignment model
- A lead adopter project, with San Diego Association of Governments (SANDAG), to use the ideas from the SHRP2 C04 project to provide pricing and travel-time reliability enhancements to their existing ABM.

The pilot projects were evaluated using the Technology Readiness Level (TRL) framework that had been developed for the FHWA Exploratory Advanced Research (EAR) program.

Results of this work included the following:

- A demonstration of the value of agent-based modeling in several transportation system management and operations applications in Maryland.
- Several case studies of ABM-DTA integration, including analysis of the I-85 bridge collapse in Atlanta.
- Development of demonstration/training data and model in Ohio and for the FastTrips project.
- Use of the C04 reliability methodology as part of SANDAG's travel demand model.
- Demonstration of the use of Technology Readiness Levels to evaluate the pilot projects.
- Significant exposure at professional conferences, such as the Transportation Research Board Annual Meetings, the Innovations in Travel Modeling Conference, and the Transportation Planning Applications Conference.

1 Introduction

In 2007, the Transportation Research Board published Special Report 288: Metropolitan Travel Forecasting. The report was produced by a committee with expertise including the relationship of travel forecasting to public policy and planning, the development of applied travel forecasting models, the application of travel forecasting models, and independent academic research on travel forecasting. The committee reported that present limitations of metropolitan travel demand forecasting models included the lack of feedback between the supply and demand side of forecasting models, insufficient model validation, and insufficient documentation or training for using advanced models. The committee then recommended improvements to the state of practice in metropolitan area travel demand forecasting by Metropolitan Planning Organizations (MPOs) and State departments of transportation (State DOTs). Some of these recommendations include implementing formal peer reviews of MPOs' modeling practice, forming partnerships between MPOs and universities, providing enhanced documentation of advanced modeling practices used by MPOs, and continued support to MPOs from the federal government by providing funding for the continued development, demonstration, and implementation of advanced modeling approaches.

Around this time, practitioners began recognizing the need to develop integrated travel demand models with detailed temporal and spatial resolution. The traditional models of that time used coarse time-periods (typically, morning peak, midday, afternoon peak, and night). As such, they were not sufficiently sensitive to travel behaviors and network conditions, and they were unable to represent the effects of policies such as variable road pricing. Integrated models represent demand changes and network performance better by modeling peak spreading, mode choice, destination choice, and the effects of capacity and operational improvements such as signal coordination, freeway management, and variable tolls.

Figure 1 Managed Lane (Source: Florida DOT)

To address these needs, the past decade has seen the development of activity and agent-based demand models[1], which represent the activities and trips of individuals in households. To address network performance with detailed temporal resolution, dynamic traffic or transit assignment models have been developed. These models represent the effects of trips on the transportation system.[2]

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[1] Two sources of introductory information on activity-based models include Castiglione et al., *Activity-Based Travel Demand Models: A Primer*, and the activity-based model page in the Travel Forecasting Resource (http://tfresource.org/Category:Activity-based_models). Agent-based models are discussed in section 1.1.2 of this report.

[2] Two sources of introductory information on dynamic traffic assignment include Chiu et al., *Dynamic Traffic Assignment: A Primer*, and the dynamic traffic assignment page in the Travel Forecasting Resource (http://tfresource.org/Dynamic_Traffic_Assignment)

This report is focused on several efforts to integrate activity/agent based demand models with dynamic traffic/transit assignment.

1.1 Relevant Past Work

Between 2009 and 2015, several activities () set the stage for the four pilot TravelWorks integrated modeling projects (C10) that are described in this report. The four pilots built upon the lessons learned from two earlier SHRP2 integrated model projects, designated as C10A and C10B. The earlier C10 projects, several agent-based modeling projects, and the development of Technology Readiness Levels, are discussed below.

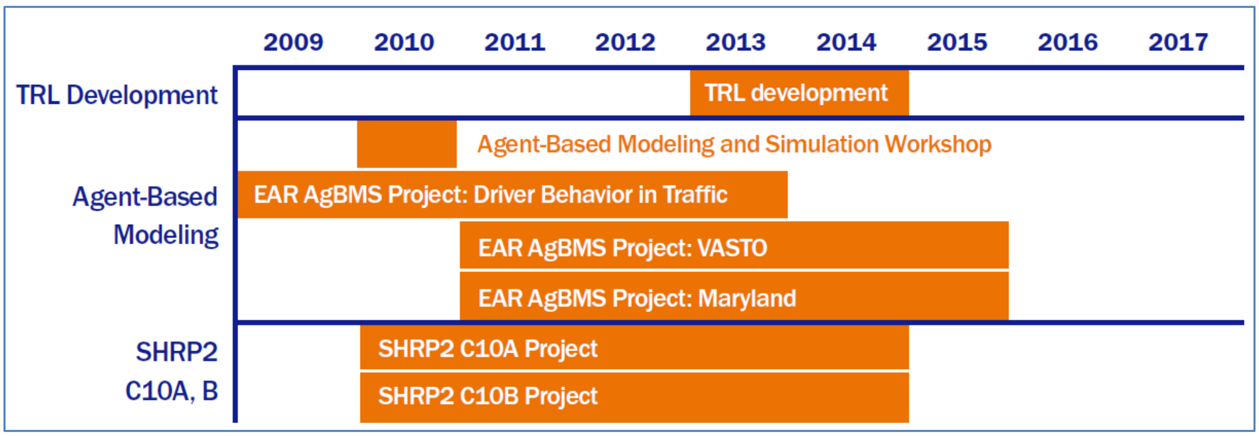

Figure 2 Timeline of Previous Projects (Source: Volpe Center)

1.1.1 Technology Readiness Level (TRL) Development

In 2014, the FHWA Exploratory Advanced Research (EAR) Program worked with the Volpe Center to develop and deliver the Technology Readiness Level for Highway Research (TRL-H) scale (Kuehn, 2017). The TRL-H was designed to meet the EAR Program's need for a system for describing the maturity of highway research products; such a system would allow experts and non-experts to document and communicate the maturity of the research at a specific point in time; understand how their research might relate to other research; and know what steps might advance the maturity of a given research project. The TRL-H is based on a scale originally developed by the National Aeronautics and Space Administration and later adapted by other Federal Agencies, and is framed by a set of questions ordered to represent increasing technology readiness for deployment. There are nine readiness levels (Figure 3) which fall into four broader characterizations: basic research, applied research, development, and implementation.[3]

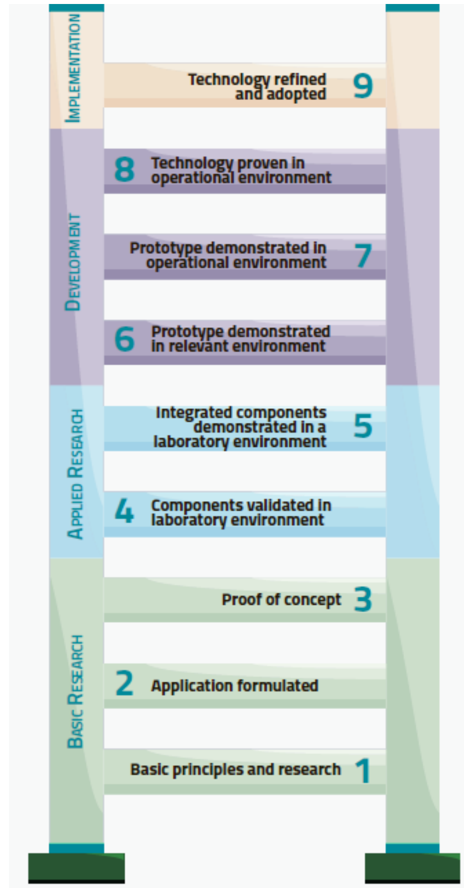

Figure 3 Technology Readiness Levels (Source: TRL Guidebook)

1.1.2 Agent-Based Modeling

The first application of the TRL-H scale to work relevant to advanced models took place in 2015, after the FHWA sponsored two EAR projects that focused on developing an agent-based modeling software framework. Two TRL-H assessments were performed on these projects. The 2015 TRL-H panels included representation from academia, government, and industry. In the first panel assessment, on the Evolutionary Agent System for Transportation Outlook (VASTO) software suite developed by University of Arizona, researchers concluded that the technology presented met requirements for TRL-H level 4 (components validated in laboratory environment) and partially met requirements for level 6 (prototype demonstrated in relevant environment). They noted a key barrier to achieving a higher TRL-H level was that the model had not been tested using real-world data, and they further recommended that the modeling framework in VASTO be applied to scenarios with behavioral responses to advance the TRL-H level. Furthermore, the panel found that the EAR projects established a baseline for researching the application of agent-based modeling and simulation (AgBMS) to transportation, and demonstrated that applying AgBMS to transportation would be achievable using existing data collection methods.

The second TRL-H assessment examined the Agent-Based Approach for Integrated Traveler and Driver Behavior Modeling presented by University of Maryland researchers. This framework included

[3] Appendix A of this report and the EAR program website (https://www.fhwa.dot.gov/advancedresearch/trl_h.cfm) contain more detail on TRLs.

contributions towards methods for modeling multidimensional agent-based travel decision-making processes at the microscopic individual level; in aggregating micro-level behavioral rules and interactions into system-level statistics for analysis and applications; and a novel dynamic behavioral user equilibrium (BUE) approach that improves run time and guarantees convergence in integrated models. The panel agreed that the project met TRL-H level 3 (proof of concept) and in order to advance the technology readiness, the researchers should clearly identify system applications, end user requirements, and performance metrics; clearly describe the user interface and input data requirements; and provide more technical documentation of the work done.

FHWA also sponsored the development of *A Primer for Agent-Based Simulation and Modeling in Transportation Applications*, published in November 2013. The primer reviewed agent-based modeling and simulation (AgBMS) applications that had emerged in transportation studies in the preceding decades, described general modeling frameworks and commonly shared procedures, and outlined the strengths and weaknesses of AgBMS. The primer also drew comparisons between the individual-based agent models and simulation-based dynamic traffic assignment approaches. For instance, both systems use some sort of simulation as a network loading method to measure travel time. It also suggested the basis of an integrated model: both systems could run iteratively to accomplish a convergence and consistency between the travelers' route choice decisions and the network-wide traffic performance.

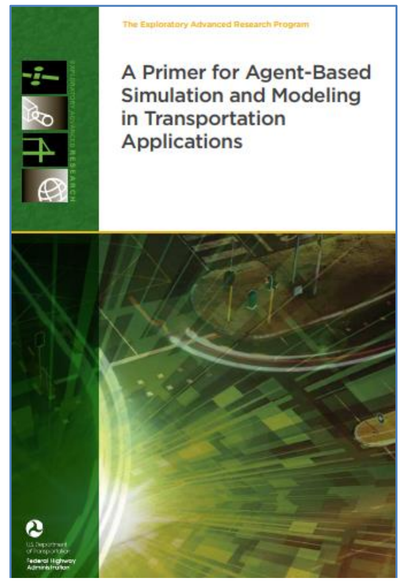

Figure 4 Primer for Agent-Based Modeling

1.1.3 SHRP2 Research: C10A and C10B

The (C10A and C10B) projects of the first SHRP2 bundle modified and joined existing activity-based travel demand and dynamic traffic assignment (DTA) models for the pilot locations of Jacksonville and Tampa, Florida, and Sacramento, California, respectively. These pilots emphasized open source software in order to facilitate broader transfer of research experience.

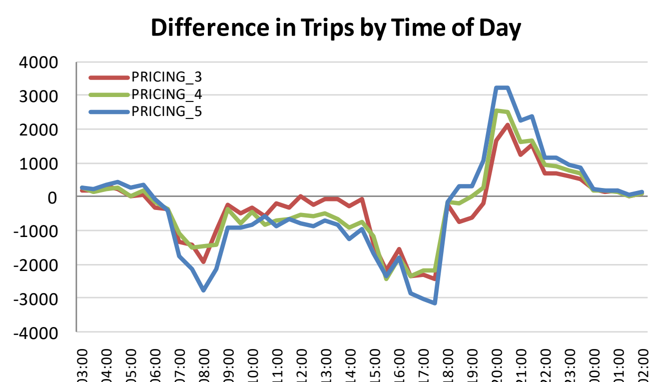

Figure 5 Selected C10A Results: Difference in trips from base scenario, for several freeway tolling scenarios (Source: RSG C10A report, 2013)

The C10A project, in Jacksonville, integrated the DaySim ABM and the TRANSIMS detailed highway routing model. A smaller demonstration model was also created for Burlington, Vermont. Later, this work was transferred to Tampa, Florida. The C10B project, in Sacramento, integrated the SACSIM/DaySim ABM, DynusT (a DTA model) and Fast-Trips, a dynamic transit assignment model.

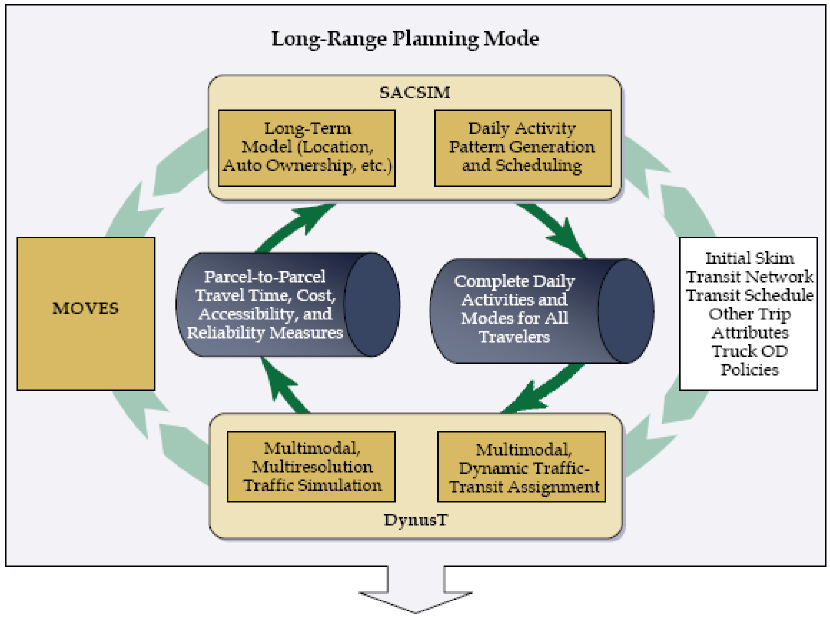

Figure 6 C10B Model Structure (Source: SHRP2 C10B presentation, 14th TRB National Transportation Planning Applications Conference, 2013)

Although the Jacksonville and Sacramento projects produced reasonable results, they were also ambitious efforts with several challenges that emerged:

- Regions may vary widely in data readiness. These models use detailed networks.
- Run times were often lengthy
- There are outstanding questions on convergence, validation and sensitivity analysis.

The projects discussed later in this report attempt to address some of these issues.

1.2 Remainder of this Report

This capstone report presents an overview of the four C10 technology pilots initiated during the implementation assistance phase of SHRP2, which did not require use of open source software. This report summarizes the investigations performed to determine the current state of practice, the selection of the four pilot projects, and how the TRL-H process was adapted from previous applications. This report discusses the major technical contributions of the pilot projects and remaining issues that the teams and panel participants have identified. It also highlights the impacts to the field that these projects have made and outreach strategies that the teams have used to share their key contributions and findings. The report concludes with next steps for research in integrated model development. Finally, descriptions of each pilot project and their contributions, accompanying publications, and documented TRL-H evaluations are included in an appendix.

2 What was Done

2.1 Laying the Groundwork

Several actions were taken before the C10 and C04 projects were awarded in late 2014. They included surveys of MPO current state of practice, a request for information from industry, and an implementation planning workshop.

2.1.1 MPO Surveys on the State of Practice

In 2007, a web-based survey of more than 200 MPOs was conducted on behalf of the Transportation Research Board (TRB). At that time, the majority of MPOs were using trip-based, four-step travel-forecasting procedures. A few MPOs were using activity-based, or tour-based models (ABM). The decade since that original survey has seen greater adoption of ABMs, with some use of DTA.

In 2011, a peer exchange on Modeling and Analysis Needs and Resources for Small Metropolitan Area Transportation Planning explored the state of transportation modeling and analysis practice in communities with populations under 200,000 (small MPOs). Since the majority of MPOs are small, it is important to understand their activities and priorities.

- All participants were involved in some form of travel demand modeling, with approximately one third of them using microsimulation. Several had included additional modes (such as transit), and others were very interested in doing so in the near future. All the MPOs were interested in land use and air quality models. In the smaller MPOs, the need for modeling is often sporadic.
- Though requirements exist for travel modeling to support air quality conformity analysis and Federal Transit Administration (FTA) programs for major transit infrastructure investments (New Starts and Small Starts), the primary application of travel models was for needs determined by each agency without explicit regulatory or program requirements.
- There is an interest in using models for operational issues, including ramp metering, signal coordination, and transit priority.
- The small MPOs reported that the traditional problem of meeting future travel demand is only one of several major challenges they face. There is interest in using models to help analyze economic impact, operations, land use, air quality, safety, and other issues.
- The small MPOs found that the familiar four-step models may not be sufficiently detailed or flexible without modification.
- Advanced approaches such as Dynamic Traffic Assignment (DTA) and microsimulation, that enable modelers to investigate solutions such as ramp metering, signal synchronization, and other methods for increasing road capacity, are being increasingly implemented.

In 2015, Cambridge Systematics, Inc. prepared a report intended to form the basis for the development of a strategic plan for the Metropolitan Washington Council of Governments (MWCOG)/ National Capital Region Transportation Planning Board (NCRTPB), entitled: Status of Activity-Based Models and Dynamic Traffic Assessment at Peer MPOs. The report defined "peer" MPOs to be within the top 20 MPOs by population (e.g., NCRTPB is 9th), plus three smaller MPOs known for innovation (Sacramento Council of Governments, Portland Metro, Mid-Ohio Regional Planning Commission). This composition makes it a reasonable set to look at for the state-of-the-practice because the more complex problems that larger MPOs face tend to drive innovation.

Main conclusions from the analysis include:

- Approximately 70 percent of the surveyed peer MPOs were using or developing an ABM.
- Although there are several aspects of transportation planning that aggregate trip-based models address well, ABMs have the ability to more effectively address complex policy questions and they are well suited for use with dynamic traffic assignment and network simulation models.
- More practical experience implementing ABMs for multiple agencies has significantly reduced the time and cost required to develop an ABM.

- DTA was not yet state of the practice, particularly at the regional level; only two of the 23 peer MPOs were using it in production.

2.1.2 Request for Information from Industry

In August 2013, the Federal Highway Administration (FHWA) Office of Acquisition Management released a Request for Information (RFI) to collect consultant and software developer perspectives on the use of advanced travel analysis tools. Details of the RFI, including the questions asked, can be found by visiting the Federal Business Opportunities website at www.fbo.gov and using the Advanced Search form to search Archived Documents for Solicitation Number (SOL#) DTFH61-13-RI-00010.

FHWA received 10 responses from respondents with significant and relevant experience in surface transportation modeling. Respondents reported on their experience with activity-based models and on dynamic traffic/transit assignment. They noted that the SHRP2 C10A and C10B projects raised awareness and expectations among modelers, but also noted several concerns:

- The learning curve for MPOs and the higher overhead that comes with increased model system complexity
- The low fidelity of the DTA processes used in SHRP2 C10, compared with traffic microsimulation
- The lack of availability of “open source” software, and the need for independent testing
- Licensing arrangements.

One respondent noted that the “most important aspect of advanced integrated model systems is that they significantly broaden the set of policy and investment alternatives that can be systematically evaluated.”

Several respondents mentioned ease-of-use. Having tools that are accessible and easy-to-use will help reduce the barrier to entry and encourage more agencies, particularly smaller MPOs, to use and apply these resources. Improving ease-of-use will enable these tools to have a wider impact. Aspects include:

- Smooth interface between supply and demand (possibly via format specification or reference implementation)
- Good technical support on a well-established platform
- Visualization and reporting
- Computational efficiency

Respondents also noted that the model system should facilitate good forecasting practices. It needs to support sensitivity analysis, and allow for validation of the feedback between ABM and DTA platforms.

2.1.3 Implementation Planning Workshop

On February 4-5, 2014, 24 representatives from TRB, AASHTO, FHWA, the Federal Transit Administration (FTA) and other Federal agencies, State Departments of Transportation (State DOTs), Metropolitan Planning Organizations (MPOs), local transportation agencies, academia, and the private sector participated in an Implementation Planning Workshop (IPW). The scope of the IPW included four SHRP2 capacity products, collectively known as Advanced Travel Analysis Tools:

- C04, Improving the sensitivity to travel demand models to travel time reliability and pricing

- C05, Understanding how operational improvements affect highway capacity
- C10, Integrating activity-based models with dynamic traffic/transit assignment
- C16, Quickly assessing the travel demand impacts of land use, investment and policy scenarios

During the workshop, participants noted that the previous ABM work in Jacksonville in connection with C10A is influencing modeling elsewhere in Florida. They also emphasized that C10 is not about promoting software products; rather it supports a methodology. For example, Jacksonville recently replaced the open source TRANSIMS (used in C10A) with TransModeler (a commercial product) in the modeling system that they had developed for C10A. IPW participants shared that MPOs already using the CT-RAMP ABM may prefer to continue using CT-RAMP rather than switching to the DaySim ABM that was used in the earlier C10 projects. IPW participants also identified some outstanding issues related to the C10 work, including challenges that emerged during the C10A and C10B research. These included

- Regional variation in data readiness
- Less familiarity among planners with DTA
- Lengthy model run times
- Unresolved questions on convergence, validation, and sensitivity analysis
- The possible need for more detailed model inputs to accurately forecast future conditions.

IPW participants then developed goals, strategies, and tactics for this SHRP2 national implementation of Advanced Travel Analysis Tools. When budgets for these projects were initially set at the TRB, FHWA and AASHTO executive levels, it was envisioned that most of the budget would go to the C10 integrated model pilots. IPW participants agreed that the majority of available funding should go to the C10 pilots. They also agreed to five high-level goals, and developed dozens of proposed tactics in support of these goals.

> *Goal 1: State DOTs, MPOs, and other transportation planning agencies use advanced travel analysis models to help inform many levels of agency decision-making, from project selection to programming and implementation.*
>
> *Goal 2: Agencies can make effective use of modeling systems at lower cost, due to improved usability.*
>
> *Goal 3: Use of advanced travel analysis models is more widespread among agencies.*
>
> *Goal 4: Advanced travel analysis models are developed for the long run, with agencies taking ownership.*
>
> *Goal 5: Modeling staff have an increased knowledge of advanced travel analysis models, including how to calibrate, validate, and run the models.*

This workshop, and the Implementation Plan[4] that came out of it, laid the groundwork for the project

[4] Implementation Plan, Advanced Travel Analysis Tools (C10/C04/C05/C16), 28 May 2014

selection process.

2.1.4 Project Selection

In May 2014, as part of Round 4 of SHRP2 implementation assistance, State DOTs and MPOs were invited to apply for implementation assistance for the following SHRP2 products:

- C10 - Partnership to Develop an Integrated, Advanced Travel Demand Model and a Fine-Grained, Time-Sensitive Network (Pilot, up to $700,000)
- C04 - Improving our Understanding of How Highway Congestion and Price Affect Travel Demand (Lead Adopter, up to $150,000)
- C05 - Understanding the Contribution of Operations, Technology, and Design to Meeting Highway Capacity Needs (Lead Adopter, up to $150,000)
- C16 - The Effect of Smart Growth Policies on Travel Demand (User Incentive up to $50,000)

Requirements for all recipients included the following:

1. Application to a significant problem that calls for the use of advanced modeling methods
2. Data and methodology publicly available
3. Commitment of State DOT and/or MPO leadership to test, and (if the test is successful) to adopt these methods
4. Participation in product evaluation activities including assessment conducted by an independent consultant for FHWA
5. Willingness to share knowledge with other organizations
6. Willingness to participate in regional or national knowledge-sharing events to promote the product

In addition, C10 applicants were asked to

1. Demonstrate an example of an ABM / DTA integration, e.g., regional DTA with time-dependent routing
2. Document on how the use of advanced tools can fit into the planning process
3. Advance in the state of practice, as evidenced by
   - Integration of methods from C04, C05, and the SHRP2 reliability projects L02, L05 or
   - Application to a problem that can't be addressed via static methods, or
   - Delivered product that addresses outstanding issues with C10: run time, convergence, calibration, validation
   - Use of tools, such as data hubs, to improve model integration.

Twenty applications were received for C10, three for C04, and three for C16. In July 2014, a panel of experts, with representation from State DOTs, MPOs, AASHTO, TRB and FHWA, reviewed the applications. Although there were many well qualified applications, in order to stay within the budget constraints, they selected four C10 projects, one C04 project, and three C16 projects.

2.2 Selected C10 and C04 Projects

SHRP2 provided implementation assistance to four pilots and one lead adopter to explore advanced integrated models, with the following projects (Figure 7):

- Two pilot projects, with Atlanta Regional Commission (ARC) and Ohio DOT, to integrate an activity-based model (CT-RAMP) with dynamic traffic assignment (DynusT) in a highway setting
- A pilot project, with Maryland State Highway Administration and Baltimore Metropolitan Council (BMC) to integrate the University of Maryland agent-based model (AgBM) with dynamic traffic assignment (DTALite), as well as a BMC's activity-based model (INSITE) with dynamic traffic assignment
- A pilot project, with Metropolitan Transportation Commission (MTC), San Francisco County Transportation Authority (SFCTA), and Puget Sound Regional Council (PSRC), to implement the Fast-Trips dynamic transit passenger assignment model[5]
- A lead adopter project, with San Diego Association of Governments, to use the ideas from an earlier SHRP2 project[6] to provide pricing and travel-time reliability enhancements to their existing ABM[7].

The projects were initiated in late 2014 with planned durations of two years for the pilots and 18 months for the lead adopter. The bulk of activity took place in 2015 and 2016. In addition to the outreach activities described in section 4.2 of this report, project teams stayed in touch with each other via quarterly conference calls. Further coordination occurred between the Ohio and Atlanta projects as they were using similar underlying models and the same consultant team.

The appendices provide further details on the C10 pilot projects.

[5] See the project website http://fast-trips.mtc.ca.gov/ for more information

[6] TRB SHRP2 Report S2-C04-RW-1, Improving Our Understanding of How Highway Congestion and Pricing Affect Travel Demand, DOI: 10.17226/22689, 2013.

[7] The final report for the C04 Lead Adopter project has been posted at http://tfresource.org/Category:Pricing_and_valuation Scroll to the bottom of the page for a link.

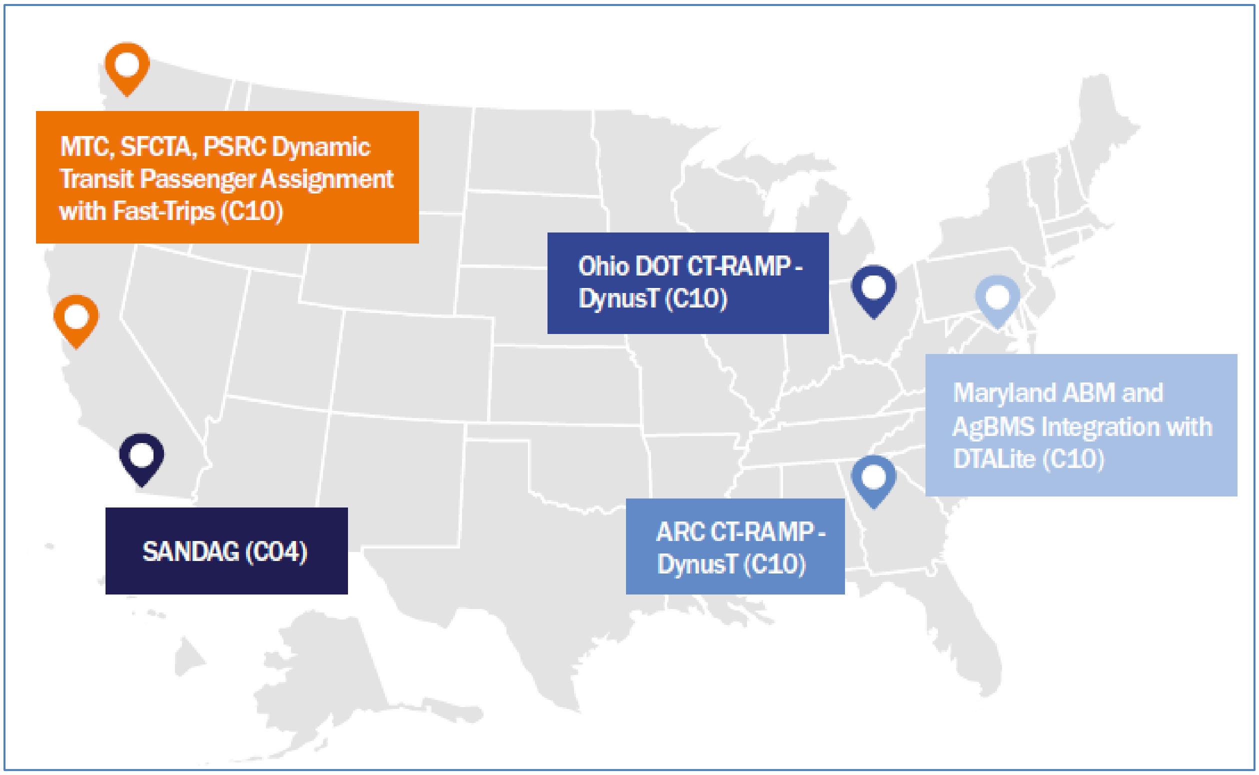

Figure 7 Selected C04 and C10 Projects (Source: Volpe Center)

2.3 Project Evaluation

2.3.1 Third Party Readiness Assessment

In 2016, FHWA contracted with Resource Systems Group (RSG) to perform a readiness assessment on the integrated tools, with the question being: how easy would it be to use these tools in other regions? They documented major inputs and outputs for each model. Not surprisingly, they found that more work needs to be done with documentation and (in some cases) with code modification to transfer the tools to other regions.

2.3.2 TRL Evaluation

The nature of these projects warranted a formal evaluation process of the readiness of the technology for further deployment. Fortunately, the FHWA Exploratory Advanced Research (EAR) program had recently introduced Technology Readiness Levels (TRL) for EAR projects (see section 1.1.1). TRLs, originally developed for NASA and DoD projects, provide a common language for assessing the readiness of a technology for deployment, all the way from basic research, to applied research, to development and implementation. They were adopted for the SHRP2 C10 projects, and provided a structure for TRL evaluations of the Maryland, Atlanta/Ohio and Fast-Trips projects.

Each TRL evaluation provided an in-depth introduction to the project to a panel of five outside experts. As was expected for these large pilot projects, the technology readiness was in the middle of the scale. An earlier version of the Maryland agent-based modeling work was reviewed in 2015. At that time, it was moving from basic to applied research. Now, it is moving from applied research to development.

Panel recommendations included specifically identifying the questions that integrated models can uniquely address, comparing integrated model results with traditional model results, and formalizing run time and convergence criteria for the integrated models.

The appendices to this report provide further information on the TRL process and on each project.

3 Technical Issues and Contributions

3.1 Defining Transportation Networks

Models with fine-grained time and space resolution call for detailed networks and calibration data at a matching time and space resolution. Challenges include time-varying elements of the network (for example, managed lanes with variable tolling), intersection controls and effectively using the newer commercial data sources on both network configuration and network performance.

Because it is needed for incumbent four-step travel demand models, information that is readily available includes:

- Nodes
- Links, with capacity, number of lanes, and free flow speed
- Zones, which provide the origins and destinations for travel demand

Additional information required for a DTA model includes

- Intersection controls and their characteristics (e.g., signal phasing and timing)
- Turning lane configurations and turning movement restrictions
- Added pocket lanes at intersections
- Accurate representation of roundabouts
- Ramp meters
- Time-dependent tolls for high-occupancy toll lanes

The loading of the network also requires a greater degree of realism than simply placing flow on an artificial link that leads to a major intersection (an approach that will almost certainly fail). Rather, a better approach is to associate several links with a zone (e.g., the links within and bordering the zone), and then load flows onto those links. This, to some extent, mimics traffic entering from a driveway or parking lot. Furthermore, since the DTA model is time-sensitive, the temporal distribution of the network loading also requires care.

Adding the required details to a network involves significant manual effort. Methods used to gather the required information included speaking to the road owners (local jurisdictions), examining aerial photographs, examining street-level photography, obtaining signal phasing and timing files, and field visits. Methods used to make the effort more manageable included use of multi-resolution networks, use of default signal phasing/timings for most locations, and creation of a link between Synchro signal files and the DTA.

3.1.1 How the Projects Addressed Network Definition

Maryland is making use of a multi-resolution network. Level 1 (Statewide) includes selected roads. Level 2 (Regional) is used for the Baltimore Metropolitan Council planning model. It includes major roads and traffic analysis zones. Level 3 is used for subarea analysis. It includes all public roads and goes to the census block level. Level 4 includes parcels.

Ohio MORPC (Columbus MPO) uses their standard regional model Cube network and Cube Junction files, supplemented with Synchro microsimulation files in the downtown area to generate DynusT DTA network and DTA intersection files. Ohio DOT has developed statewide network file standards for all MPOs to use that include relatively detailed roadway operation attributes such as pocket lanes, turn prohibitions, signal timing, sign locations, and time of day parking restrictions. They also developed a Network Calculator utility to estimate the number of lanes available for travel and time of day capacity values.

Atlanta started with a NAVTEQ[8] street centerline network file and developed their routable network in-house. Although defaults were used for most of the 5000+ signals in the network, actual signal phasing and timing (from Synchro) was used on selected corridors. They also attached traffic message channel (TMC) codes with the network, to facilitate matching with INRIX[9] data.

To facilitate use of signal data, Metropia enhanced DynusT to read Synchro signal files.

This leaves the issue of future-year network configuration. Atlanta is using a master network approach, where future years can be switched on or off. FHWA has also initiated a project to develop methods for predicting future signal configurations in a network.

Transit networks present their own issues, which were explored in the Fast-Trips project. The Fast-Trips team developed an extension to the General Transit Feed Specification (GTFS), called GTFS-PLUS[10]. GTFS-PLUS builds GTFS to enable dynamic transit passenger assignment. For example, it adds information on access modes (walk, drive or bike) and fares.

3.2 DTA-ABM Integration

3.2.1 Concepts and Issues

Integration is straightforward in the traditional 4-step demand model with static assignment. The 4-step model sends trip tables to the static assignment model, while the static assignment model returns level-of-service (LOS) skims for all trips. With a limited number of time periods each day (typically: AM Peak, PM Peak, midday, night), and a spatial resolution at the traffic analysis zone level, the static assignment model can produce level-of-service skims for all possible trips.

[8] A commercial product, now part of HERE,

[9] A commercial product

[10] See https://github.com/osplanning-data-standards/GTFS-PLUS, http://fast-trips.mtc.ca.gov/library/T2-NetworkDesign-StaticCopy-Sept2015V0.2.pdf and https://www.sfcta.org/sites/default/files/content/IT/SFCHAMP/PDFs/2016_ITM_GTFS-Plus.pdf

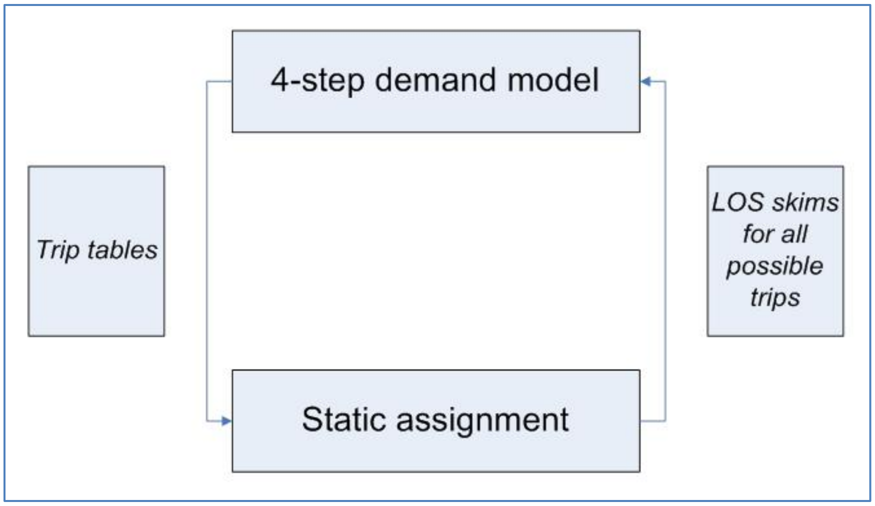

Figure 8 Integration in a 4-step Static Model (Source: tfresource.org)

Rather than working with aggregated trip tables, the integrated activity based model (ABM) and dynamic traffic assignment (DTA) model deals with individual trips. Because they are disaggregate models, they can include very detailed person and household attributes, such as value of time. The ABM works with household activities and explicitly represents the linkages among activities and travel across multiple persons in a household. In an environment where evaluating the effects of managed lanes with tolls is an important application, the model must consider that the value of time may be different among travelers, thus leading to different route and departure time choices.

The DTA model takes the trips from the ABM and produces network performance by a specific time-of-day. This provides the trip travel times that are fed back to the ABM.

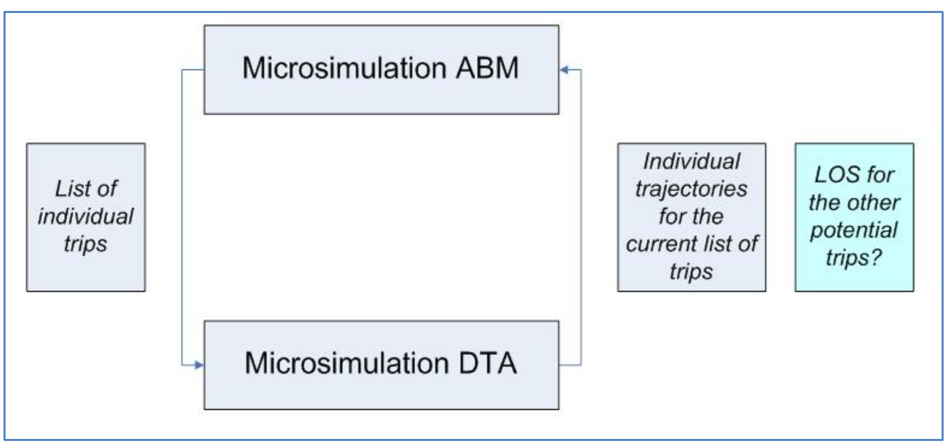

Figure 9 ABM-DTA Integration (Source: tfresource.org)

There are two issues that need to be resolved for an ABM-DTA integration to be successful.

First, an activity-based model works with chains of trips and activities that have specific times and durations. The congested travel times that are returned from the DTA may lead to schedule inconsistency. Consider an example where the traveler has the following activities:

- Travel from home to work, departing at 7:30 AM, estimated trip duration is 30 minutes

- Fixed start time of 8 AM at work, with a work duration of 9 hours ending at 5 PM (fixed)
- Travel from work to shopping, estimated at 30 minutes
- Shopping starts at 5:30 PM (not a fixed time), and takes 15 minutes (fixed)
- Travel from shopping to home, estimated at 15 minutes
- Arrive at home at 6:00 PM.

Now, suppose that the travel from home to work, and the travel from work to shopping takes 45 minutes, rather than the originally estimated 30 minutes. This will lead to a violation of the work start time constraint, and will lead to an arrival home later than 6 PM. The modeling framework needs to resolve these violations; it might do so by adjusting schedules (just as a worker might leave home a bit earlier in order to arrive at work on time), as is explained in the next section.

The second issue results from the disaggregate nature of the models. While in a traditional 4-step model, a set of travelers going from traffic analysis zone (TAZ) A to TAZ B during the AM Peak could be treated as a single group, in a disaggregate model, these same travelers will be split into many groups, each with different travel characteristics:

- The TAZs may be split into micro-analysis zones, or even parcels
- The AM Peak will be split into a large number of smaller time intervals
- Finally, the travelers themselves may have differing value-of-time, which will also affect route choice (e.g., a traveler with high value-of-time may choose a toll facility)

The number of combinations of origin/destination/time interval/traveler value-of-time quickly becomes unmanageable, making the use of conventional skims impractical. Rather, a combination of skims and individual trajectories are used, as is explained in the next section.

3.2.2 What Did the Ohio and Atlanta Projects Do to Address the Issues?

Two methodologies developed for the C10 project that assist in the integration of the DTA and ABM model results are the individual Schedule Adjustment Module (iSAM) and the Accumulated Database of Individual Trajectories (ADIT)[11]. They work within two loops (Figure 10), an outer loop (Loop 1) and an inner loop (Loop 2). The outer loop 1 generates activity patterns and schedules, while the inner loop 2 simulates the activity patterns, adjusts schedules, and evaluates travel “stress” measures for use in Loop 1.

[11] http://tfresource.org/images/4/48/ITM16_Integrated_Model_of_Travel_Demand_and_Network_Simulation.pdf

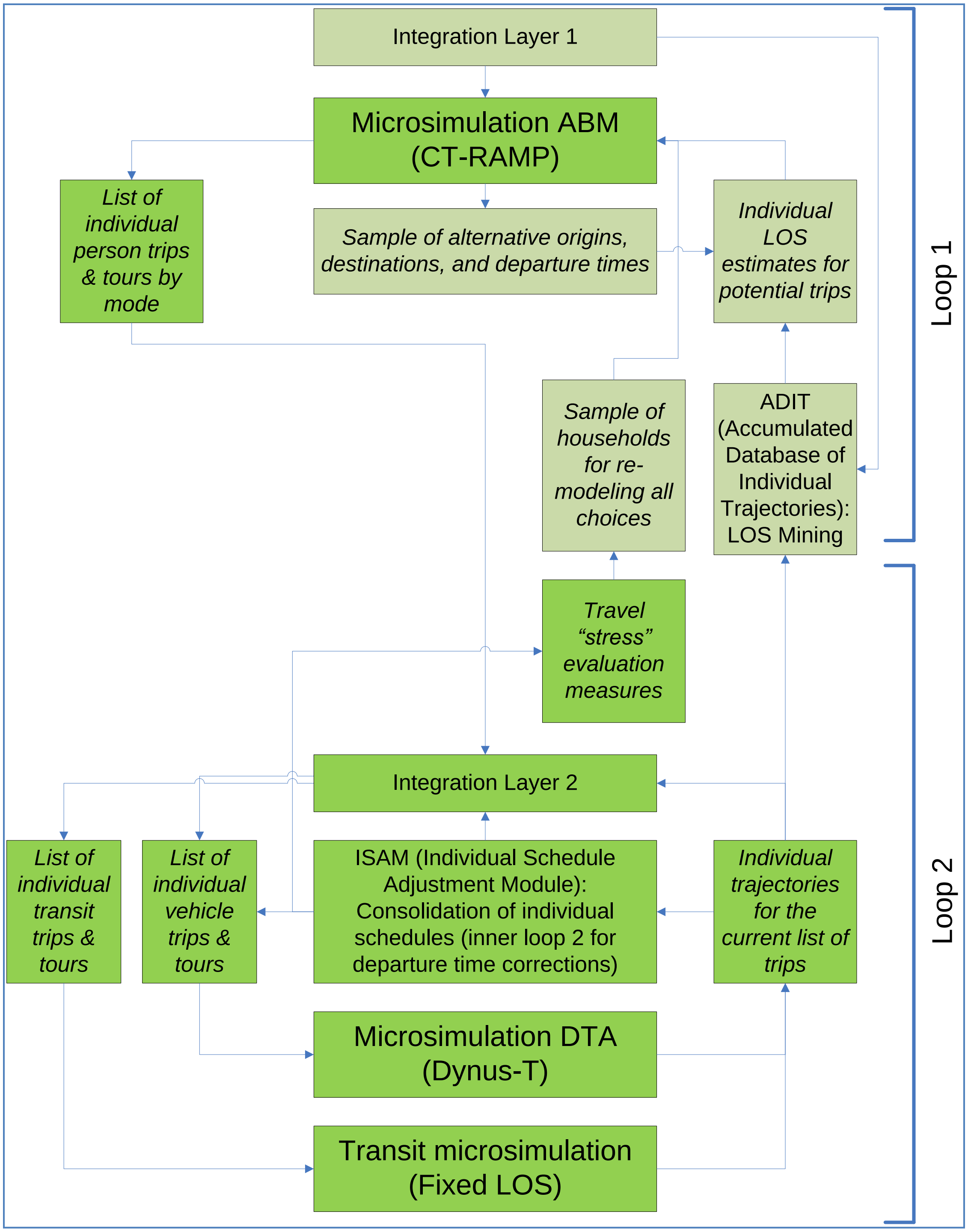

Figure 10 ABM - DTA Integration (Source: Vovsha et al, 2016 Innovations in Travel Modeling Conference)

The iSAM routine is run after the DTA, and can quickly adjust the start, end, and duration of trips that are output by the ABM. The functionality of the iSAM is best illustrated by recalling the example from section 3.2.1 where a traveler is attempting to travel to work, and then go shopping. Table 1 illustrates how iSAM will fix that traveler's schedule inconsistencies.

Table 1 Schedule Adjustments

Activity	Original schedule	Schedule after DTA produces congested travel times	Issue	Schedule as adjusted by iSAM
Depart home	07:30 AM	07:30 AM		07:15 AM
Arrive at work	08:00 (fixed time)	08:15 AM	Violates work start time of 08:00	08:00
Depart work	05:00 PM (fixed time)	05:00 PM	Violates work duration of 9 hours	05:00 PM
Arrive at shopping	05:30	05:45		05:45
Depart shopping	05:45	05:45	Violates shopping duration of 15 minutes	06:00
Arrive at home	06:00	06:00		06:15

iSAM is part of an inner loop that uses multiple runs of the DTA to ensure schedule consistency. Outputs of this inner loop include the adjusted trajectories for the list of trips, and travel "stress" evaluation measures (e.g., whether a traveler is spending an excessive amount of time in travel status).

The accumulated database of individual trajectories (ADIT) is used in place of travel time skims. When the DTA model estimates the travel time for an origin-destination (O-D) pair, it provides information not only for that pair, but for intermediate points along the route.

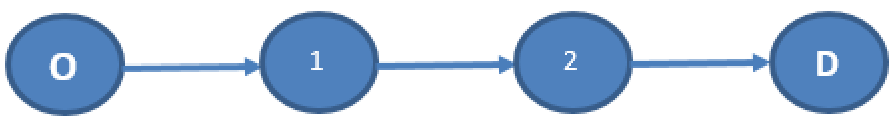

Figure 11 Trip with Intermediate Points

In the example above, travel time information is available not only for the O-D trip, but also for the O-1, O-2, 1-2, 1-D and 2-D trips. A large number of trajectories is produced, requiring the use of efficient data structures. Rules are also required to match new trips to trajectories that are "close enough", both in time (within 5 minutes, 15 minutes, or 60 minutes), and in space (same micro-analysis zone (MAZ) pair, or same traffic analysis zone (TAZ) pair). In tests with the Mid-Ohio Regional Planning Commission (MORPC) model in Columbus, the majority of trips found representative trajectories better (closer match) than conventional skims[12].

3.3 BUE and Agent-Based Modeling

A common assumption in travel modeling is that travelers choose the available route having the least generalized cost (often simplified to travel time). User equilibrium is reached when no traveler can unilaterally improve their own generalized cost by changing routes (Wardrop, 1952). It is assumed that travelers have perfect knowledge and are willing to search for the best route. In dynamic traffic assignment, this principle is extended to establish the equilibrium condition for each departure time, so

[12] Slide 12 from March 2016 C10 quarterly call, and Slide 16 of November 2016 presentation at a C10 quarterly call.

that a dynamic user equilibrium (DUE) is established (Chiu et al. 2011). Finding a DUE can take substantial computational time. Further, in an agent-based environment with integer flows, perfect convergence will never be reached.

3.3.1 What Is Behavioral User Equilibrium (BUE)?

Travelers are assumed to be intelligent agents, with socio-demographic attributes, experience with travel, knowledge about the transport network, and subjective beliefs based on memory. These beliefs include a perceived expected gain from searching for a new mode, departure time or route. As agents gain experience, their beliefs will change. Note that such a modeling framework is flexible: the model may search for model, departure time, pre-trip route or enroute diversion, or even driving style.

At each iteration, the relevant attributes of the agents are updated based on travel experience. They then choose whether or not to search for a new mode, departure time, or route, based on the perceived gain from the search. If the perceived gain along all dimensions is zero or less, then the agents continue their habitual behavior. If the gain along at least one dimension is greater than zero, then a search occurs along that dimension. Searching stops when the cost of the search exceeds the perceived gain. Convergence is modeled as a day-to-day learning process, and is reached when the perceived gain from searching drops below the search cost for all agents.

Since the key concepts include Search, Information, Learning and Knowledge, this agent-based model has been named the SILK Travel Behavior Model, or SILK AgBM.

3.3.2 Modeling Framework Using BUE

The SILK agent-based model of traveler behavior is then integrated with a dynamic traffic assignment model (DTALite). DTA produces the travel experience (Figure 12) that is then sent back to the agent-based model.

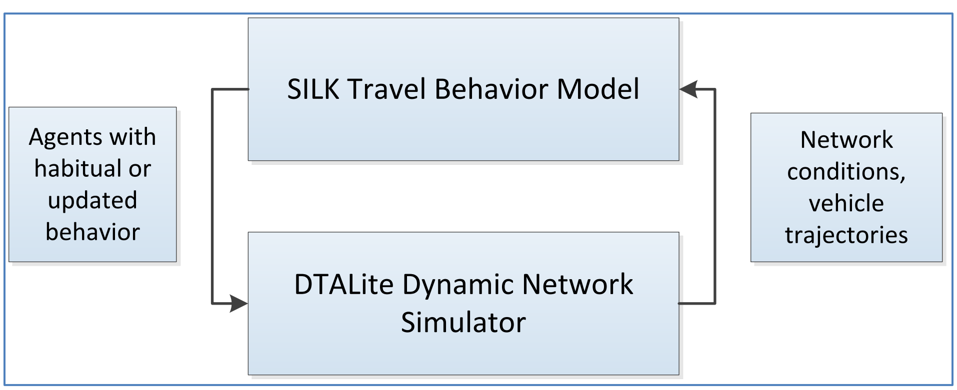

Figure 12 SILK AgBM - DTALite Framework (Source: Volpe Center)

Figure 13 shows the modeling framework as it was implemented in Maryland.

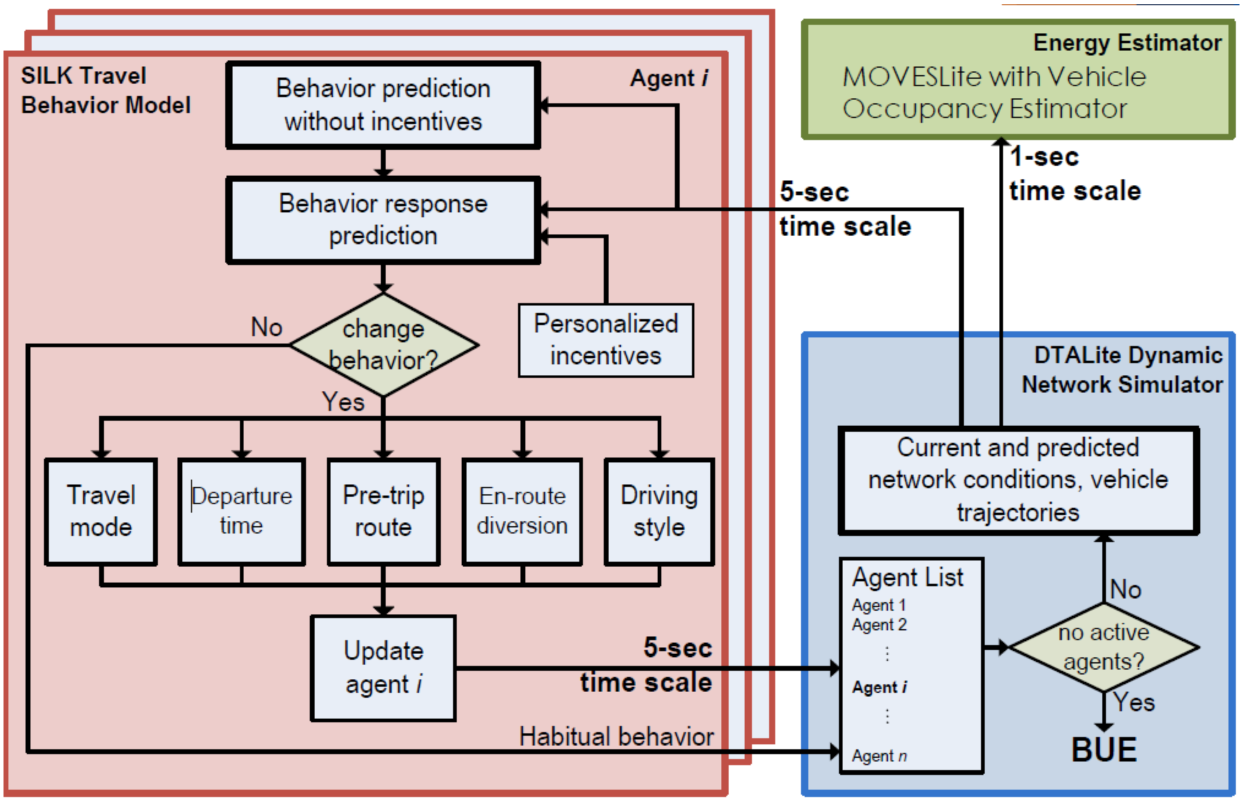

Figure 13 Framework as Implemented in Maryland (source: Maryland TRL peer review presentation)

The SILK AgBM framework is promising for two reasons:

- It can capture non-equilibrium situations; e.g., a temporary disruption where it is not realistic to assume that travelers have perfect knowledge of potential alternate routes.
- As a satisficing framework, it has the potential of a faster convergence than that of a DUE optimizing framework, while still producing realistic results.

3.3.3 What Did the Maryland Project Do?

The Maryland project demonstrated that the BUE concept works well for predicting how travelers adapt new travel patterns in response to system changes such as operational improvements in a corridor, new development patterns, or addition of a new toll road (Figure 14). At this point, Maryland is not using the agent-based model for long-range planning.

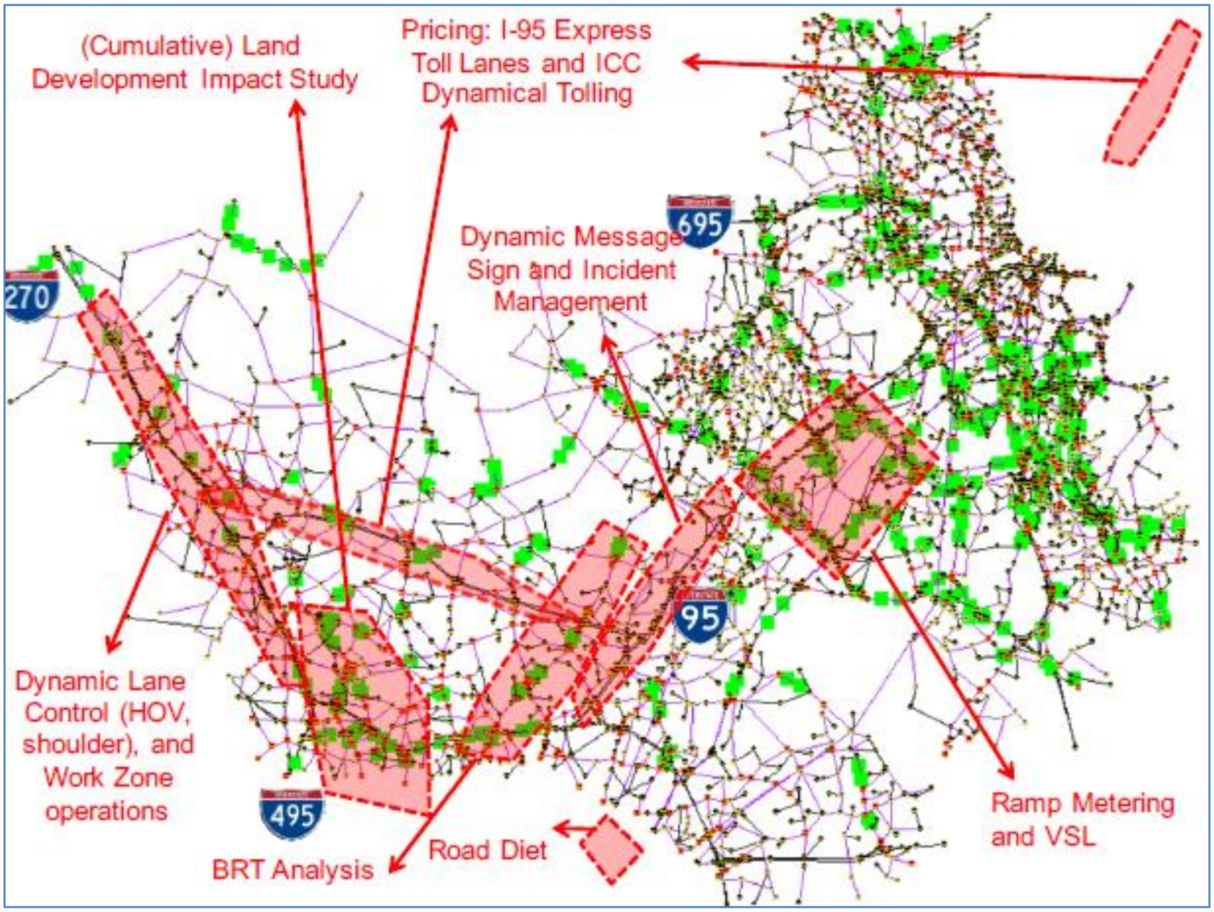

Figure 14 SILK AgBMS - DTALite Applications (source: Maryland TRL peer review presentation)

One promising application area is in Transportation Systems Management & Operations (TSM&O) projects, including those related to pricing, dynamic lane control, ramp metering, and incident management. Other applications include the effects of new land uses, analysis of a bus rapid transit (BRT) corridor, and analysis of a road diet.

Run-times were assessed with 8 million agents and 30 million trips in the DC-Baltimore region, with the model running an order-of-magnitude faster than real time. It can support real-time decision-making at the corridor and subarea levels. Validation results also met the team's internal targets, with comparison of volumes and speeds between modeled and observed.

Table 2 Maryland Integrated Model Validation

Measure	Target	Observed
Freeway traffic counts estimation error	10%	9.6%
Arterial traffic counts estimation error	15%	14.2%
Travel time validation	20%	13.1%
Travel speed validation	20%	12.7%
Vehicle level energy use	25%	10%

3.4 Dynamic Transit Passenger Assignment

The projects discussed previously are primarily concerned with automobile travel on highways. The MTC/SFCTA/PSRC project[13] is concerned with transit. The need was for a tool that could address transit crowding and reliability, so that these factors may be adequately considered when evaluating investments and policies. Models of passenger activities in complex capacity-constrained transit systems have several challenges. First, when one considers both time and space, a passenger may have an enormous number of possible paths through the system. These paths may use different types of services. For example, seven different types of transit, with three transit operators, are shown in Figure 15, which depicts a few blocks in downtown San Francisco:

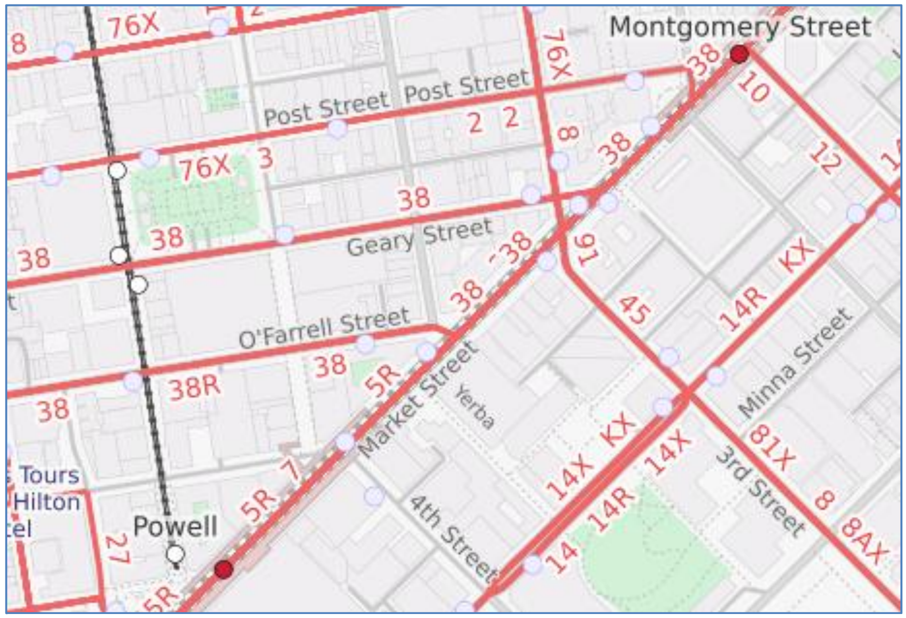

Figure 15 Portion of a Transit Network (Source: Openstreetmap)

- Local bus service with a variety of headways, operated by SFMTA
- Limited stop bus service (e.g., 38R)
- Express bus service (e.g., KX, operated by SamTrans)
- Cable car
- Surface trolley car (on Market Street)
- Underground light rail (running under Market Street)
- Underground heavy rail with its own fare structure (BART, also running under Market Street)

The paths through the transit system are discrete (because transit uses discrete vehicles that make stops at specified locations) and also stochastic (because these vehicles may be early or late). The paths also may be capacity constrained, as some vehicles may be full. Transit usage typically involves payment of one or more fares, though the majority of systems have free or discounted transfers; thus, the fares are ***not*** additive on the links that comprise the path. These characteristics of transit make it difficult to model dynamic transit passenger assignment.

3.4.1 What Did the MTC/SFCTA/PSRC Project Do?

Fast-Trips is a dynamic transit passenger assignment model that is schedule-based and considers transit capacity. For this project, the code was rewritten to improve run times and maintainability. It was also

[13] http://fast-trips.mtc.ca.gov/

enhanced to consider detailed non-additive fare information (such as free transfers), because fares are an important policy lever. Accomplishments of the project included the following:

- The multi-agency effort forced the team to address documentation early on. They created a detailed project website, and a glossary of definitions
- The team added numerous additions and refinements to the Fast-Trips model
- The team developed an extension to the General Transit Feed Specification (GTFS) network standard suitable for dynamic transit modeling
- The **Fast**-Trips model has been tested with corridor data in San Francisco
- The team developed dwell time model specifications for bus systems in the Puget Sound Region (King County Metro) and the San Francisco Bay Area (Muni, operated by the San Francisco Municipal Transportation Agency, SFMTA) to reflect the dynamic nature of dwell time for simulating realistic transit travel times
- The team developed teaching materials and held a tutorial at the TRB National Planning Applications Conference in 2017

During this project, the team, supported by a panel of experts, reviewed both the needs of the project and relevant literature. They identified several significant technical challenges (documented in a presentation "Dynamic Passenger Assignment Challenges" at the 2017 TRB Annual Meeting[14]), and have proposed a plan to engage researchers to address them. Key research needs include

- More efficient path search algorithms for transit
- Handling service unreliability in schedule-based dynamic transit trip assignment
- A computationally efficient transit passenger route choice model that does not make unrealistic assumptions about passenger behavior.

[14] http://fast-trips.mtc.ca.gov/library/TRB17-Issues.pdf

4 Impacts

4.1 Maturity of Agent-Based Modeling

Starting in 2010, the FHWA Exploratory Advanced Research program sponsored a workshop and several projects on agent-based modeling for transportation. At that time, the projects were still considered to be basic research, moving into applied research. For example, in a 2015 Technology Readiness Level (TRL) peer review the work in Maryland achieved a level of 3, as a proof-of-concept, ready to make the transition from basic to applied research. The 2017 peer review (discussed later in this report in Appendix B: Maryland SHRP2 C10 Pilot) found that the work had reached level 5, as applied research, ready to move into development.

4.2 Outreach

National outreach activities included the TRL peer review meetings (section 2.3.2 of this report), five Travel Model Improvement Program (TMIP) webinars, and presentations at the 2016 Innovations in Travel Modeling Conference, the 2016 Association of Metropolitan Planning Organizations (AMPO) annual meeting, and the 2017 Transportation Planning Applications Conference (Table 3). Note that access to some of the hyperlinks in Table 3 require logging into the TRB Annual Meeting Online website.

Furthermore, the TRL peer review meetings (section 2.3.2) provided in-depth exposure to the pilot projects to selected experts, from academia, consulting industry, and MPOs, who were not part of the projects.

Table 3 Presentations, Workshops and Webinars with a National Audience

Activity	Date
Workshop: C10 Integrated Models at the 6th Innovations in Travel Modeling (ITM) Conference in Denver, Colorado	1 May 2016
Presentation: Pricing and Reliability Enhancements in the San Diego Activity-Based Travel model, at the 6th ITM Conference in Denver	3 May 2016
Presentation: Integrated Model of Travel Demand and Network Simulation, at the 6th ITM Conference in Denver	4 May 2016
SHRP2 The Work Workshop: PlanWorks, EconWorks, and TravelWorks, at the 2016 AMPO Annual Conference in Fort Worth, Texas	25 October 2016
TRB Paper: 17-05722 Dynamic Passenger Assignment Challenges, presented at the 2017 TRB Annual Meeting	10 January 2017
TRB Paper: 17-06397 Making Open Transportation Data Useful and Accessible: Recommendations for Good Practices in Open Data Standards Management, presented at the 2017 TRB Annual Meeting	10 January 2017
TRB Paper: 17-05904 Developing an Activity Based Statewide Model by Expanding a Regional Model, presented at the 2017 TRB Annual Meeting	10 January 2017
TMIP Webinar: Enhanced Methods to Forecast Travel Behavior in Response to Travel Time Reliability and Pricing	18 January 2017
TMIP Webinar: Integration of Dynamic Traffic Assignment with Agent-	15 March 2017

Activity	Date
based and Activity-based Modeling in Maryland	
TMIP Webinar: Deep Integration of Activity-Based Modeling and Dynamic Traffic Assignment, using CT-RAMP and DynusT	5 April 2017
Tutorial: Dynamic Transit Assignment from Scratch: A Tutorial, at the 2017 Transportation Planning Applications Conference in Raleigh, North Carolina	14 May 2017
Visualization Workshop: Presentation on FastTrips, at the 2017 Transportation Planning Applications Conference in Raleigh	
Session: Integrated Dynamic/AB Models: Getting Real Discussion, at the 2017 Transportation Planning Applications Conference in Raleigh	15 May 2017 (Monday 3:30 PM)
Presentation: Using Surveys for Dynamic Transit Calibration. at the 2017 Transportation Planning Applications Conference in Raleigh	16 May 2017
Presentation: Real-Time Metering Control and Behavior Responses: An Agent-Based Travel and Traffic Microsimulation Approach, at the 2017 Transportation Planning Applications Conference in Raleigh	17 May 2017
TMIP Webinar: Theory and application for transit, using FastTrips, in San Francisco and Seattle	24 May 2017
TMIP Webinar: ABM/DTA integrated models in Ohio and Atlanta	7 June 2017
TRB Paper: 18-03713 An Integrated, Validated, and Applied Activity Based-DTA Model for the Baltimore-Washington Region, presented at the 2018 TRB Annual Meeting	9 January 2018
TRB Paper: 18-05502 Integrated Model of Travel Demand and Network Simulation, presented at the 2018 TRB Annual Meeting	10 January 2018

4.2.1 Local Outreach

In addition to the national activities mentioned earlier, projects have engaged in local outreach activities. Atlanta is communicating with its constituent counties. Integrated ABM-DTA was the topic of an Ohio statewide user group meeting in early 2017. Maryland is sponsoring several training sessions.

4.3 Applications

Applications of the integrated models include:

- A before / after study of the I-85 bridge closure in Atlanta,
- Several transportation system management and operations (TSM&O) projects in Maryland (discussed in section 3.3.3), and
- Use of Fast-Trips to model transit line crowding and other service concerns in downtown San Francisco.

In late March 2017, a bridge on I-85 in Atlanta collapsed due to a fire. For a period of more than a month, motorists were required to find alternate routes, until the road was re-opened in May 2017. Significant data were available, including traffic volumes, speeds and origin-destination information. The integrated model was used to examine the effects of the collapse, including use of alternate routes (Figure 16).

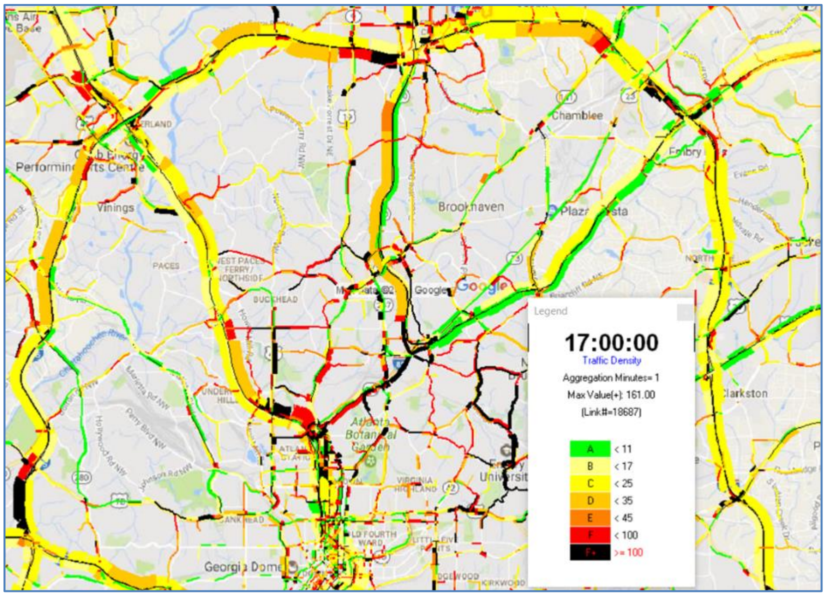

Figure 16 Atlanta Traffic Density and Volume after I-85 Bridge Closure (Source: ARC)

Finally, Ohio DOT is using the SHRP2 C10 package to develop an integrated model for a small city (Lima), and will release it for training and demonstration purposes.

5 Next Steps

Several project teams are now developing documentation and training for their local stakeholders. They are working with FHWA to develop demonstration and training data sets. The TravelWorks product team will also be developing case studies that highlight both the technical advances and applications of the integrated models. Finally, FHWA has initiated a project to develop a method for predicting future signal configurations in a network.

6 References

Cambridge Systematics, Inc. "Dynamic, Integrated Model System: Sacramento-Area Application Volume 1: Summary Report," 2014.

Cambridge Systematics, Inc. "Status of Activity-Based Models and Dynamic Traffic Assignment at Peer MPOS," 2015. Retrieved from https://www.mwcog.org/file.aspx?D=4I4c3V5tz1NX%2FJ1mRm8ngNOP2lR2IlINP0s86mxTxP4%3D&A=bwpDgpuaidJbqzIA61InNBxuu%2BQ9vpwRkOWn4SIhySU%3D on 11 April 2018.

Castiglione, Joe, Bradley, M., Gliebe J. *Activity-Based Travel Demand Models: A Primer*. Washington, D.C.: Transportation Research Board, 2014. https://doi.org/10.17226/22357.

Chiu, Yi-Chang, Bottom, J., Mahut M., Paz, A., Balakrishna, R., Waller, T., and Hicks J. *Dynamic Traffic Assignment: A Primer*. Transportation Research Circular, E-C153. Transportation Research Board, 2011. http://onlinepubs.trb.org/onlinepubs/circulars/ec153.pdf.

Deshmukh-Towery, N., Machek, E., Thomas A. *Technology Readiness Level Guidebook.* Report FHWA-HRT-17-047, 2017.

Kuehn, D., "Assessing Technology Readiness Levels to Increase Implementation," in TR News, number 310, July-August 2017

National Research Council (U.S.), and Committee for Determination of the State of the Practice in Metropolitan Area Travel Forecasting. *Special Report 288: Metropolitan Travel Forecasting: Current Practice and Future Direction.* Washington, D.C.: Transportation Research Board, 2007. http://www.trb.org/Main/Blurbs/158933.aspx

Resource Systems Group. *Dynamic, Integrated Model System: Jacksonville-Area Application*. Washington, D.C.: Transportation Research Board, 2013. https://doi.org/10.17226/22482.

Rossi, T., Zyntarakis, M. "SHRP C10B: Partnership to Develop an Integrated Advanced Travel Demand Model with Fine-Grained, Time-Sensitive Networks," 14th TRB National Transportation Planning Applications Conference, 2013.

Wardrop, J.G. "Some theoretical aspects of road traffic research," Proceedings of the Institution of Civil Engineers, Part II, volume 1, number 2, pages 325-378, 1952

Zhang, L. "Behavioral Foundation of Route Choice and Traffic Assignment: Comparison of Principles of User Equilibrium Traffic Assignment Under Different Behavioral Assumptions." *Transportation Research Record: Journal of the Transportation Research Board* 2254 (2011): 1–10. https://doi.org/10.3141/2254-01.

Zheng, H., Son, Y.-J., Chiu, Y.-C., Head, L., Feng, Y., Xi, H., Kim, S., Hickman, M. *A Primer for Agent-Based Simulation and Modeling in Transportation Applications* (No. FHWA-HRT-13-054). 2013. Retrieved from https://www.fhwa.dot.gov/advancedresearch/pubs/13054/13054.pdf

Acronyms

AASHTO	American Association of State Highway and Transportation Officials
ABM	Activity-Based Model
ADIT	Accumulated Database of Individual Trajectories
AgBM	Agent-Based Model
AMPO	Association of Metropolitan Planning Organizations
ARC	Atlanta Regional Commission
BMC	Baltimore Metropolitan Council
BUE	Behavioral User Equilibrium
DoD	Department of Defense
DOT	Department of Transportation
DTA	Dynamic Traffic Assignment
DUE	Dynamic User Equilibrium
EAR	Exploratory Advanced Research
FHWA	Federal Highway Administration
GTFS	General Transit Feed Specification
IPW	Implementation Planning Workshop
iSAM	Integrated Schedule Adjustment Module
ITM	Innovations in Travel Modeling
LOS	Level of Service
MORPC	Mid-Ohio Regional Planning Commission
MPO	Metropolitan Planning Organization
MTC	Metropolitan Transportation Commission
NASA	National Aeronautics and Space Administration
ODOT	Ohio Department of Transportation
PSRC	Puget Sound Regional Council
RFI	Request for Information
SANDAG	San Diego Association of Governments
SFCTA	San Francisco County Transportation Authority
SHRP2	Second Strategic Highway Research Program
SILK	Search, Information, Learning and Knowledge
TAZ	Traffic Analysis Zone
TRB	Transportation Research Board
TRL	Technology Readiness Level
TRL-H	Technology Readiness Level - Highway
TSM&O	Transportation Systems Management & Operations

Appendix A: Technology Readiness Levels

In 2013, the FHWA Exploratory Advanced Research (EAR) program sponsored development of a framework using Technology Readiness Level for Highway Research (TRL-H). TRLs are based on similar scales used by other agencies, such as NASA and the Department of Defense, to measure the progress of a technology towards maturity. The TRL scale provides a structured approach for assessing the maturity of a technology, and can thus inform reasonable next steps for bringing that technology closer to deployment. It provides an approach for experts and non-experts to communicate about the status of a new technology, enabling realistic expectations to be set for someone wishing to adopt the technology.

Technology readiness levels were used to evaluate several EAR agent-based modeling projects, including the original EAR-sponsored work on Maryland's agent-based model. Given the complexity of the SHRP2 C10 projects, the TRL-H approach was chosen for their evaluation.

Table 4 shows the TRLs as they were adapted for the C10 projects.

Table 4 Technology Readiness Levels

	TRL	Description	To achieve the given TRL, you must answer yes to EVERY question. Discuss any uncertain answers.
Basic Research	**1**	**Basic principles and research**	• Do basic scientific principles support the concept? • Has the technology development methodology or approach been developed?
	2	**Application formulated**	• Are potential system applications identified? • Are system components and the user interface at least partly described? • Do preliminary analyses or experiments confirm that the application might meet the user need better than legacy static models?
	3	**Proof of concept**	• Has desired system performance (e.g., run time, computer requirements) been defined? • Is system (the model, method, or software) feasibility fully established? • Do experiments or modeling and simulation validate performance predictions of system capability? • Does the technology address a need or introduce an innovation in the field of transportation?
Applied Research	**4**	**Components validated in laboratory environment**	• Are end user requirements documented? • Does a plausible draft integration plan exist and is component compatibility demonstrated? • Were individual components successfully tested in a ***laboratory environment***[15] with credible results? • Can we expect that computational requirements, memory requirements and run times will be manageable for the full-size model (in a larger region)?
	5	**Integrated components demonstrated in a laboratory environment**	• Are external and internal system interfaces documented? Have model inputs, outputs, and configurations been documented? • Are target and minimum operational requirements (convergence, run time, etc.) developed? • Is component integration demonstrated in a laboratory environment (*i.e.,* a fully controlled setting)?
Development	**6**	**Prototype demonstrated in relevant environment**	• Is the operational environment fully known (*i.e.* user community, physical environment, and input data characteristics as appropriate)? • Was the prototype tested in a realistic environment outside the laboratory (*i.e.* ***relevant environment***[16])? • Does the prototype satisfy all operational requirements when confronted with realistic problems? • Is the prototype able to assess the relevant policy questions? • Are the input data for the models readily available? • Can the models be adequately calibrated and validated? How do the results compare with the results of traditional models? • Are the requirements for supporting software and hardware reasonable?
	7	**Prototype demonstrated in operational**	• Are available components representative of production components?

[15] Laboratory Environment is that of an academic project, using real data for a small region. It may show promising results (or not), but is not influencing MPO/State DOT decision-making, nor usable immediately by an MPO or State DOT.

[16] Relevant Environment is that of an MPO or consultant project, using real data on a full-size model. The model's recommendations are not yet being used for decision-making.

		environment	• Is the fully integrated prototype demonstrated in an ***operational environment***[17] (*i.e.* real world conditions, including the user community)? Has it been run by an end user (MPO, State DOT) on real data? • Are all interfaces tested individually under stressed and anomalous conditions? • Have model configuration, inputs, and outputs to run in operational environment been documented?
	8	**Technology proven in operational environment**	• Are all system components form, fit, and function compatible with each other and with the operational environment? • Does the technology meet its stated purpose and functionality as designed? • Is the technology proven in an operational environment (*i.e*. meet target performance measures)? • Are the cost and level of effort to set up the model, validate the model, and test alternatives with the model acceptable (within reasonable range)? • Was a rigorous test and evaluation process completed successfully? • Does the end user have enough confidence in the technology to use it for decision-making? • Is it easy to use the model for testing alternative policy questions? • Can model results be readily displayed in a format that is understandable to decision makers? • Are model results consistent with what other analysis techniques predict the results should be? • Can the underlying code be maintained or modified by those other than the original developers? • Is there a process for on-going maintenance of the model software?
Implementation	**9**	**Technology refined and adopted**	• Is the technology deployed in its intended operational environment? • Is information about the technology disseminated to the user community? • Is the technology adopted by the user community?

A TRL-H assessment can be used to:

- Perform a rough portfolio analysis of the technology in terms of technical maturity
- Identify gaps in the development and testing of a technology to help advance the technology towards an implementable state.
    - What still needs to be done before practical adoption of this technology?
    - Approximately what level of effort is required to bring this technology to a useable or fully operational state?
- Communicate the maturity state of a technology to stakeholders using common language

An important part of the TRL assessment process is the panel meeting, where a group of outside experts

[17] Operational Environment is provided when the system is "owned" and run by the MPO/State DOT. Those running the model have sufficient technical expertise, and are using real-data on a full-size model with the intent of using results of the model for decision-making.

are convened (either in-person or by web conference) to review the technology and provide their assessment as to its maturity, as well as recommended next steps to advance the product's maturity. The TRL assessments were conducted for these projects in June 2017:

- Maryland, with a focus on agent-based modeling
- Atlanta and Ohio
- Fast-Trips.

Insights from the TRL process that common to the projects are described below.

There was sometimes confusion among panelists between "laboratory" and "relevant" levels of technology readiness. This language demarcates levels 5 and 6 of the TRL-H scale, which are respectively *Integrated components demonstrated in a laboratory environment* and *Prototype demonstrated in relevant environment*. Another common theme raised by panelists was the importance for project teams to identify the relevant applications of their technology: evaluated teams did this with varying levels thoroughness. A final common observation was that teams did not always report in detail their model validity and usability issues. For instance, large run time projects were often presented without a detailed discussion of how they could address this challenge, and trajectories from the model were sometimes only weakly validated, if at all.

Additionally, there were a few common recommendations found across pilot projects. A component panelists took interest in from the Ohio pilot was the Lima model, a smaller scale model that would soon be complete and self-contained. Panelists identified opportunities for technology transfer and knowledge dissemination, testing of various models and frameworks, and demonstrations through the use of the Lima model. For other projects, producing a similar small-scale model would also be useful to demonstrate readiness at TRL-H levels 4 and 5, *Components validated in laboratory environment* and *Integrated components demonstrated in a laboratory environment*. Another component that panelists wanted to see from project teams was a demonstration of the value and applicability to real world problems gained by a team's key innovation, such as BUE, trajectories, or capacity-constrained transit trip-making. The final recurring recommendation was that teams needed to present more ideas for addressing run-time issues.

Regarding the TRL-H assessment process itself, the Volpe support team noted that conducting the panel assessment remotely through conference call and webinar was just as effective as conducting the panel with a mixture of in-person and call-in participants. This is a useful observation for future TRL-H panels, as team members and panelists were often located in a variety of places. It was also noted that the technical team presentation would typically last about 1.5 hours, with at least another 1.5 hours of panel discussion and presentation of review results. This has been found to be a sufficient amount of time for the meeting, allowing for detailed project presentations and a complete, constructive panel review. Finally, a separate recap phone call between the Volpe team (who were responsible for preparing the formal TRL-H panel assessment report) and FHWA project liaisons immediately following the conclusion of the meeting was useful for summarizing the key recommendations from the panel for the report.

Appendix B: Maryland SHRP2 C10 Pilot

Description

The Maryland Integrated Travel Analysis Modeling System (MITAMS) integrates advanced travel demand models with fine-grained time-sensitive traffic network models to support agency goals in the areas of planning, integrated planning and operations, and transportation systems management and operations (TSM&O) at statewide, metropolitan, and subarea/corridor levels. The MITAMS system consists of the following components:

- Software
  - The InSITE activity based model (ABM), a type of travel demand model
  - The SILK agent-based model (AgBM)
  - The DTALite Dynamic Traffic Assignment (DTA) model
  - The integrated system: InSITE-DTALite or SILK-DTALite
- Input Data
  - Multi-resolution network, traffic signal, etc.
  - Demand (household, person, etc.)
- Output (travel times, costs, distances, etc.)

MITAMS is composed of two models. First is the integration of the Baltimore Metropolitan Council InSITE ABM with an existing statewide DTALite DTA model. Second is the integration of DTA with an Agent-Based Microsimulation Travel Demand Model (AgBM), named SILK (for its emphasis on Search Information, Learning, and Knowledge in the travel decision-making process). Both models have three components, ABM/AgBM, DTA, and the integration of the two. The DTA part is based on DTALite software for both models.

Publications

Title	Conference or Journal	Date	Presenter(s) or Author(s)
An Integrated, Validated, and Applied Activity Based-DTA Model for the Baltimore-Washington Region	TRB National Transportation Planning Applications Conference	May 15, 2017	Thomas Rossi, Cambridge Systematics, Inc.

Contributions as Presented to TRL-H Panel in June 2017

Members of the University of Maryland project team (led by Lei Zhang) provided an overview of the data hub and integrated modeling tools. The data hub provides several scales of network resolution (from corridor to statewide), and they are working on a multi-scale representation of land use. The goal is to maintain a single DTALite model for statewide, regional and subarea/corridor applications. The remainder of the presentation focused mainly on the two MITAMS integrated models, InSITE ABM-

DTALite and SILK AgBM-DTALite. The former is for use on a regional scale, and the latter on a subarea or corridor scale.

First, they discussed contributions from the development, validation, and application of the InSITE ABM-DTALite integrated model:

- The initial static highway assignment is done using CUBE, a commonly-used proprietary software; subsequent big loop iterations continue until the number of infeasible agents are reduced to fewer than 50,000.
- The model takes less than one day for a reduced sample run to five days for a full sample run.
- The model is validated with comparison to real traffic counts: overall, it is more accurate than the InSITE ABM with a static traffic assignment.
- Baltimore Metropolitan Council (BMC) applied the model to test a land-use change scenario (brownfield area in Baltimore) involving 12,000 new residents and 14,000 new jobs.

Next, they discussed the contributions of the SILK AgBM-DTALite integrated model:

- Search, Information, Learning, and Knowledge (SILK) is a quantitative modeling framework that attempts to explain how people actually make decisions. It includes subjective beliefs (based on past experience), memory, and search costs.
- The convergence criteria are based on Behavior User Equilibrium (BUE), where all agents stop searching for alternatives: the vast majority of agents decide on a mode, departure time, and route within 15 iterations.
- The model is intended for transportation system management and operations (TSM&O), including corridors and incident management.
- The model can support real-time decision-making because it can run up to 18 times faster than real-time; the greater a server's RAM, the faster the model, but this comes with increased cost.
- The model meets validation targets for traffic count and travel time, speed, and energy use estimation errors.

The integrated models have been transferred to agencies and consultants, and some applications have been developed. The MITAMS team plans to continue model validation, improving run time performance, advancing the visualizations, and developing more applications (e.g., a beta version with multi-model transit assignment and transit skims that would bypass the use of CUBE).

TRL-H Evaluation

The panel performed a Technology Readiness Level for Highways (TRL-H) assessment of Maryland Integrated Travel Analysis Modeling System (MITAMS). Although most of the discussion was focused on the SILK AgBM-DTALite integration, the panel also briefly discussed the individual components, including the InSITE Activity Based Model (ABM).

They concluded that the InSITE ABM and DTALite are at a level 6-7, or *Prototype demonstrated in relevant (level 6) or operational (level 7) environment*. The SILK AgBM-DTALite model is at level 5, or *Integrated components demonstrated in a laboratory environment*. The panel noted that the latter model is nearly at level 6, or *Prototype demonstrated in relevant environment*.

For the InSITE ABM and DTALite models at TRL-H Level 7, the panel agreed that the model and technology is becoming mature. Remaining issues to be resolved in order to reach level 7 include the following:

- Visualization of outputs is still a work in progress
- We don't know the extent to which the interfaces have been stress tested
- We don't know the extent to which model configuration, inputs and outputs have been documented for running in an operational environment. There may still be some manual interconnections.

Panel recommendations for advancing the SILK AgBM-DTALite Project included

1. Clarify the policy questions best addressed by this approach, leading to approaches for validation and sensitivity analysis to best support the identified policy questions.
2. Continue testing the BUE of the SILK model.
3. Formalize convergence criteria and run time definitions for SILK AgBM – DTA.
4. Create better visualizations of model outputs, as well as potential data mining and analysis opportunities.
5. Integrate the model with ancillary travel markets, such as external movements and trucks

Appendix C: Atlanta and Ohio SHRP2 C10 Pilot

The ARC/Ohio teams developed and applied a model system that integrates an Activity-Based travel demand Model (ABM) and Dynamic Traffic Assignment (DTA), taking maximum advantage of the disaggregate nature of both models. Rather than using skims, all interaction between ABM and DTA including generating a list of vehicle trips by ABM for DTA and providing Level-of-Service (LOS) variables by DTA for ABM is implemented at the individual level without an aggregation bias. The model is being implemented at the Atlanta Regional Commission (ARC) and Ohio State DOT (ODOT).
The system consists of the following components:

- Software
    - The CT-RAMP activity based model (ABM), a type of travel demand model
    - The DynusT Dynamic Traffic Assignment (DTA) model
    - Disaggregate replacement for skims (individual vehicle trajectories)
    - Individual schedule adjustment module (iSAM) (including linear programing software)
    - The integrated system: CT-RAMP and DynusT
- Data
    - Input (network, traffic signal, traffic data, household, person, etc.)
    - Output (travel times, costs, distances, etc.)

The integrated model system is being implemented by ARC and ODOT with data in different regions. ARC's model system is composed of an ABM model built of the Atlanta, Georgia region with a DynusT DTA model built for the same region. ODOT has the integration of DynusT DTA with the ABM model built of Columbus, Ohio as well as a small city, Lima, Ohio. Both model systems integrate ABM and DTA.

Publications

Title	Conference or Journal	Date	Presenter(s) or Author(s)
Moving towards Agent Based Model (AgBM) as the Next Step in Evolution of Integrated ABM-DTA Models	6th ITM Conference, Denver	May 3, 2017	Peter Vovsha, PB
Integrated Model of Travel Demand and Network Simulation	6th ITM Conference, Denver	May 4, 2016	Peter Vovsha, PB James E. Hicks, PB Rebekah Anderson, Ohio DOT Gregory Giaimo, Ohio DOT Guy Rousseau, Atlanta Regional Commission
Integrated ABM-DTA Model: First Application Experience and Lessons Learned	TRB National Transportation Planning Applications Conference	May 15, 2017	Peter Vovsha, WSP
Integrated ABM & DTA	TRB National	May 15, 2017	Guy Rousseau, Atlanta Regional

Title	Conference or Journal	Date	Presenter(s) or Author(s)
Models Discussion: The Atlanta Regional Commission Experience	Transportation Planning Applications Conference		Commission

Contributions as Presented to TRL-H Panel

Peter Vovsha gave a presentation on the methodology and structure of the integration layer. First, he discussed their progress towards the concept of Activity-based model (ABM) – Dynamic traffic assignment (DTA) deep integration through the application of microsimulation and individual trajectories instead of static level of service (LOS) skims. The goal is to integrate activity choice, location, and schedule with mode and route to create a complete Agent-based model. He emphasized the importance of high temporal, spatial, and typological resolution for the ABM or DTA models.
Next, Peter discussed the two loops that make up the integration layer. The first loop (external) is the CT-RAMP ABM microsimulation of activity patterns and schedules using individual LOS, and the second loop (internal) is the DynusT DTA microsimulation with the iSAM. The iSAM is a method of peak spreading and adjusting schedules for realistic trip chain loading. He also explained the concept of household stress as a behavioral gap measure, and that it is used to create the adjusted individual schedule for iSAM. The convergence and stability of the solution with iSAM is determined based on the number of people with changing trip departure times between iterations. Loop 1 uses indexing logic to determine the best representative sub-trajectory, and LOS manager to determine the travel time, toll, and distance of the trajectories. Peter concluded with a discussion on moving towards a complete AgBM, and pointed out that the ABM traditionally doesn't have a real-time implementation and response, but the team's work on the iSAM fills that gap.

Following Peter's presentation, Rebekah Straub Anderson and Guy Rousseau presented overviews of the applications of the integrated model in their respective regions and agencies, Columbus, Ohio (MORPC) and Atlanta, GA (ARC). Panelists were given an overview of the different hardware capabilities at ARC, MORPC, and WSP, and Rebekah mentioned that her agency (Ohio DOT) was considering the upgrade to 1 TB of RAM in the future, which would cost them about $20,000. The ABMs for Columbus and Atlanta were developed separately, so there are some differences: for instance, the ARC model CT-RAMP1 uses a temporal resolution of 30 minutes whereas the MORPC CT-RAMP2 is output in continuous time so it can work with DTA seamlessly. Rebekah also outlined the current runtimes in Columbus and Atlanta, and discussed how the runtimes of 18 hours to several days based on the size of the region may or may not be reasonable for them. Next, she showed the CUBE interface of a demonstration of the full model in Lima, Ohio, which the team is putting out for anyone to examine and use. They are working on making the source code available even though it involves proprietary software like CUBE and DynusT.

Guy presented several scenarios and combinations of model components that were tested in the Atlanta region: the base DTA DynusT was tested with either fixed demand or schedule adjustment via iSAM, and on a typical day and the recent I-85 bridge closure. He highlighted the work done in-house to prepare the DTA model accurately with signalized intersections and ramp meters, and the estimation and calibration of traffic flow models using speed data. Guy highlighted the change in relative gaps between the first user equilibrium iteration and the final iteration to illustrate the level of convergence that each of the four scenarios reached. For example, the base DynusT with fixed demand concluded with a relative gap of 0.11, whereas the Bridge closure scenario resulted in a final gap of 0.31 without iSAM and 0.29 with. Guy pointed out that the bridge closure convergence (or lack thereof) under a critical network condition is problematic, though including iSAM typically improves the DTA convergence. Based on these results, it appears that only changing route choice could not account for the capacity drop caused by the bridge closure, so in the future, further schedule relaxations might be necessary to increase model accuracy in extreme conditions. Finally, Guy presented a comparison of traffic counts as their method of validation.

Rebekah presented the MORPC scenarios the integrated model was tested on. She shows the trajectory coverage that they had in Columbus with very low aggregation levels: especially away from peak hours, they were able to achieve very high coverage by low levels of aggregation, and overall only 3% of trips had to be done by skims. She also showed the effects of multiple iterations on the mode choice and pointed out that despite some changes between iterations, relative to the entire population mode choice was quite stable in the Columbus region.

Finally, the team's presentation concluded with the state of their model development: deep integration or complete disaggregation is computationally feasible for small regions, and they are moving towards complete AgBM. Currently, runtime is an issue which they want to address by upgrading their hardware. They envision that a complete system transfer or partial transfer of only the integration later can be done for other interested regions. The test model in Lima is going to be released in the Fall, once they work out the challenges around using certain proprietary software. Lima is a small enough region that, the model takes only a few hours to run on a laptop, so it is easier to use as a model demonstration.

TRL-H Assessment

Although most panelists initially estimated that the readiness level was a 6 to 7, or *Prototype demonstrated in relevant (level 6) or operational (level 7) environment,* they ended at level 5, or *Integrated components demonstrated in laboratory environment,* noting that it would not be difficult to reach level 6. A discussion on whether end user requirements had been documented (1st question in level 4) and the extent to which relevant policy questions were defined led the panelists to agree that the appropriate place to begin the TRL-H assessment was lower than initially expected. For instance, the technical aspects of the model such as the methodology, some standards for convergence, and validation, as presented are currently accessible to sophisticated users. Furthermore, there was a question on the role of transit: these projects are primarily focused on highways.

The panel concluded that though there were no direct discussion by presenters on level 4 criteria, for the most part it could be assumed that the project must meet those criteria in order to achieve the level of development in their model as presented today. For instance, although end user requirements and plausible draft documentation were not explicitly presented, in order to achieve the collaboration and engagement of the two agencies and consultants, it is very likely that these aspects were defined by the team earlier on. Panelists also discussed the definitions of and the distinctions between the laboratory, relevant, and operational environment, which were useful in informing the ultimate panel level assessment. The integrated models are operating at more than a laboratory environment, because they are being used on large, real data sets. On the other hand, they are not yet at an operational environment, because the scenarios presented are not yet being used for decision-making.

In the discussion of level 5 criteria, the panel also assumed that external and internal interfaces had to exist, since the Lima model was already in development and the Lima interface was presented. The team is using informal criteria for runtimes, and the presenters acknowledged that under certain conditions such as a very large region or extreme congestion, the runtimes become prohibitively high. Furthermore, the measure of convergence by using relative gaps between first and last iterations of user equilibrium lacks context, and panelists were left wondering what the significant values was achieved upon the end of the model runs. There was also confusion regarding the number of iterations for the DTA model that the team used in the integrated model, and the team later clarified for the panelists that they used many loops, upwards of 40, to reach convergence. The panel suggested that one way to contextualize the real-world impact of the model might be to compare different scenario output with the four-step model or ABM-static assignment model to highlight any possible new insight from an ABM-DTA integrated model.

In discussion of the level 6, the panel requested clarification from the team on how the full integrated model was run, as this process wasn't discussed in the presentation. They later clarified that currently the full integration is run at WSP, and they have developed scripts that must be run in sequence in order to run the model. In careful consideration of the distinctions between relevant and operational environments, it was concluded that due to long runtime, the Atlanta model would require more powerful hardware to meet the operational needs of a realistic situation. Furthermore, neither models have been sufficiently applied to policy questions to soundly say that the models have been demonstrated in a relevant environment. The panel agreed that it should be shown that the model can be applied in situations such as regional transportation plan development, network reliability tests, and pricing scenarios more successfully than other models; for other interested agencies, this is a necessary demonstration of the potential value of the new model. On the issue of model validation, there were some metrics identified by the team such as traffic volume, travel time, and speed on links. Regarding calibration, further clarification with the team revealed that the Ohio team has defined a standardized strategy of calibrating their ABM for distinct regions in their state. Finally, a discussion on hardware concluded the level 5 assessment, with panelists acknowledging that what is to be defined as reasonable hardware requirements is constantly changing as computers become increasingly powerful. One suggested alternative was to use hardware on demand, or cloud computing services.
Panel recommendations for advancing the CT-RAMP-DynusT Integration project include:

1. Understand the application and policy questions, and show that the integrated model brings new insight and utility when answering such questions.
2. Conduct comprehensive comparisons between the integrated model and other models, such as the traditional four-step model and an ABM-static model.
3. Prepare or provide documentation for the full integrated model and its unique components.
4. Formalize the run time criteria.
5. Run the integrated model in-house to show that it is transferrable.
6. Improve the model's applicability to transit.

Appendix D: MTC SHRP2 C10 Pilot

The Fast-Trips technology implementation adds a dynamic transit passenger assignment component to a regional planning model. This integrated model system demonstrates appropriate sensitivity to service quality and capacity changes so that it can be used in evaluating planning and policy changes. The model will be flexible enough to segment transit passengers (i.e. youth, commuters, elderly etc.) and how they value various service features (time, reliability, seat availability, walking distance etc.) of each transit path component (walk access, waiting, transfers, in-vehicle time).

The integrated model system is being developed by a multi-agency collaborations from three public agencies (Tri-Agency team), Puget Sound Regional Council (PSRC), Metropolitan Transportation Commission (MTC), and San Francisco County Transportation Authority (SFCTA). The SFCTA model will be the focus of calibration, while the PSRC model will have an integrated, but not calibrated process. The models will be used to improve many transit-related projects in the Bay Area and Puget Sound regions.

The transit model system consists of the following components:

- Software and Algorithms
    - The activity based model (ABM): Travel Model One, SoundCast, and SF-CHAMP
    - The Fast-Trips schedule-based Dynamic Transit Passenger Assignment (DPA) model
    - The integrated system: Travel Model One, SoundCast, & SF-CHAMP and Fast-Trips
- Data
    - Data standards (e.g., extensions to GTFS)
    - Input (Transit network, demand, route, and performance data for the Bay Area and Puget Sound regions)
    - Output (travel times, costs, distances, etc.)

The integrated model system is being implemented in both the Bay Area and Puget Sound regions, with calibration being done on SFCTA's SF-CHAMP system. The three existing ABM travel forecasting tool include: MTC's Travel Model One, PSRC's SoundCast, and SFCTA's SF-CHAMP. The model system integrates Fast-Trips into the existing travel forecasting tools from these agencies. The integrated model system represents transit accessibility and passenger behavior at a fine-grained level within their respective activity-based travel demand models in the Bay Area and Puget Sound regions. Note that integration within MTC's Travel Model One [and successors] is outside the scope of this project.

Publications

Title	Conference or Journal	Date	Presenter(s) or Author(s)
Making the Leap: Agency-led integrated team and other methods of technology transfer	6th ITM Conference, Denver, Colorado	May 3, 2016	Elizabeth A. Sall, UrbanLabs LLC Diana Dorinson, Transportation Analytics David Ory, Metropolitan Transportation Commission Billy Charlton, Puget Sound Regional Council Joe Castiglione, San Francisco County Transportation Authority
Developing usable and useful travel modeling software	6th ITM Conference, Denver, Colorado	May 3, 2016	Elizabeth A. Sall, UrbanLabs LLC Lisa Zon, Metropolitan Transportation Commission Billy Charlton, Puget Sound Regional Council
Dynamic Passenger Assignment Challenges	TRB 96th Annual Meeting	January 8-12, 2017	Lisa Zorn, Metropolitan Transportation Commission Elizabeth Sall, UrbanLabs LLC
Dynamic Transit Assignment from Scratch: A Tutorial	TRB National Transportation Planning Applications Conference	May 14, 2017	Lisa Zorn, Metropolitan Transportation Commission Elizabeth Sall, UrbanLabs LLC Drew Cooper, San Francisco County Transportation Authority Andisheh Ranjbari, University of Arizona

Contributions as Presented to TRL-H Panel

Elizabeth Sall delivered the presentation entitled “Implementing Dynamic Transit Assignment: A Tri-Agency Experience,” which overviewed Fast-Trips technology and software, capability of localization or technology transfer, and deployment. Elizabeth highlighted project teams which included members from the Metropolitan Transportation Commission (MTC), Puget Sound Regional Council (PSRC), and San Francisco County Transportation Authority (SFCTA), with support from researchers and consultants. She also explained the different Fast-Trip applications or outcomes each of the three agencies seek: for MTC, the DPA model itself, for PSRC, integration with their Activity-based Model for PSRC, and for SFCTA, calibration for San Francisco. Fast-Trip team’s goals are for the software to be *usable* for future users of the model, *useful* especially with an advantage over static assignment, and theoretically sound and mathematically elegant. The goal of localization is to identify and apply performance measures, data needs and a calibration approach for specific applications. The deployment goal is to provide applications to the long range forecasting, transit planning, and research communities. There have been numerous sub-teams working simultaneously; currently, the teams on networks, localization, software, and implementation are still working with management and communication teams on the project.

For Fast-Trips software and implementation to be usable it must be easy to understand, fix and modify. It is preferably open source, with a fast-enough runtime, a user community, and complete documentation. The team has primarily implemented it in Python using the *pandas* package. They still use C++ (its original implementation language) for the pathfinding algorithm due to some limitations of Python run times for non vector operations. Fast-Trips can be run directly in the terminal through Python, once the user has set up their inputs and configurations. Elizabeth also briefly discussed the tutorials the team gave on the software at the TRB National Transportation Planning Applications Conference (May 2017), where many people were able to implement Fast-Trips on their own laptop computers; the team benefitted greatly from the opportunity to test the software on a range of devices and is now in the process of addressing bugs they discovered. In terms of software performance, the team was able to run a small sample of 2687 person trips in a 2.4 hours on an MTC machine, with the majority of time spent in pathfinding. Assuming a naive linear scaling of runtime with respect to person-trips or paths, the team projected that with 1.7 million passengers (2040 daily average demand forecast in the Bay Area), the model would take a total of 63 days (1200 hours in pathfinding and 316 hours in simulation) to run. Similarly, with 41 million paths that are defined by zone to zone (origin-destination, OD) pairs, the model would take 1522 days to run. The team reasoned that because the original calibration was run with no market segmentation and included finding every possible path, a more reasonable future algorithm will trim the path set to only the most likely paths; thus, the scaling of runtime in reality will be less than linear.

The model is defined by 3 loops: global, pathfinding, and simulation. The simulation loop uses the network, demand, pathweights, and run parameters as inputs to find time-dependent trip-based hyperpaths, assign and simulate passenger flow based on the path, update costs (dwell time), and iterate until converge. The pathfinding loop is used to generate pathset for unassigned passengers. A trip-based hyperpath is based upon the time window of a passenger departure, feasible paths with and their associated probabilities, waiting times and non-travel times, and a specified directionality which is based on desired departure or arrival time. It is essentially running a nested logit model. An important development was the addition of an accurate calculation of fares including non-additive fares due to transferring, because it is an important policy lever. A single global loop includes 3 to 5 simulation loops within 3 pathfinding loops. The team has not yet identified the appropriate equilibration criteria for the global loop. The team is still working to address issues with crowding and skimming (for ABM integration)[18]. One metric they may use for skimming is the logsum associated with travel cost in the mode choice model. Future refinements of the model may challenge the first-come first-serve assumption for transit vehicle boardings and alightings (prioritize the most desperate waiting passengers), allow variable passenger density, and differentiate between the cost of sitting and standing.

The remaining software and implementation challenges the team has identified include addressing bias in the path-based approach, which may be resolved with a link-based approach (subject of a TRB paper by Lisa Zorn), making skimming feasible, and resolving problems unique to transit assignment like common lines, route overlap and the effects of highly variable networks on transit reliability.

Elizabeth next shifted the presentation to progress towards localization of Fast-Trips. Not all the performance measures they propose are reasonable yet. Survey data and automatic passenger count (APC) data is necessary for calibration to a new locality. Furthermore, transit vehicle performance must

[18] Note that skimming is no longer being pursued. Current focus is on a one-way integration.

be calibrated, primarily using dwell times. Again, a key challenge that remains is incorporating the effects of vehicle reliability, such as in the case of bus bunching. One way the team is currently performing person or path level calibration is by comparing every single path generated by the model with an actual person's trip (that comes from on-board survey or APC data), and identifying discrepancies between the observed and the model. One thing they have already noticed is that their model tends to allow too many transfers. Once that is complete, they will be able to calibrate the model with transit loads predicted by the model and actual transit load data. The team's next steps for calibration also include calibrating loads and crowding based on full demand from travel model, and using the travel model in feedback loop.

Finally, Elizabeth presented the ongoing efforts in deployment. She primarily discussed applications for transit agencies, cities, and MPOs, although she noted that this model could also be of use to a transportation network company (TNC). In transit planning, Fast-Trip could be a standalone tool for service planning, to planning for robustness in the event of schedule changes or special events. It could also be used in planning studies for near-term forecasting. The most difficult application they have identified is for long range planning with MPOs, who would be interested in the model once it is integrated with an ABM.

TRL-H Assessment

Panel members' initial opinions about the TRL-H level mostly ranged from 2 (*application formulated*) to 3 (*proof of concept*). One member did make the case for level 4 (*components validated in laboratory environment*) or 5 (*integrated components demonstrated in a laboratory environment*) possibly being met, because the model is ready for applied research due to its extensive documentation.
The panel was in general agreement that the project met and exceeded the requirements of levels 1 and 2, the panel began a more detailed discussion at readiness level 3. At level 3, it is acceptable for Fast-Trip's desired system performance to be defined informally, although the team did have a runtime target of matching the current SF-CHAMP transit assignment run time on the same computing power. The panel agreed that the algorithm and methodology as a concept was feasible, although several panel members expressed concerns that the team's projected runtimes would render the model as it is currently envisioned infeasible in practice. However, the panel did agree that for level 3, proof of concept, the feasibility condition was met. Furthermore, because the team did indeed produce detailed individual trajectories for their calibration sample, the panel agreed that Fast-Trips was capable of simulating the time-dependent use of transit, in a setting with complex route choice competition and capacity constraints.

In discussions of sufficiency for achieving readiness level 4, the panel lauded the Fast-Trip team's documentation efforts, and careful definitions of the different applications of their model and the corresponding end users. Furthermore, they agreed that a "draft integration plan" condition is implicitly met as SFCTA and PSRC have already run the model on sample data, and close communication and collaboration among the three agencies of the team is evident. The panelists discussed the implications of runtime and computational requirements on the manageability of the model. Again, the concern was raised that the model has only been tested on a small sample of passengers, so in the future the team will need to prove their model on a larger system. The panel also discussed the issue of skims and how the lack of skimming capability currently prevents the team from achieving one desired application, an integrated model with ABM. However, they ultimately agreed not to focus too heavily on the skimming issue because it is not central to what the team is doing. Instead, the panel shifted their discussion to readiness for service planning acknowledging that though skimming will be an ongoing challenge, the model is approaching readiness for transit service planning. To continue making progress towards the transit planning application, the panel believes it should be a high priority to ensure the model can process the full demand. Once the team can demonstrate the successful application of the model under a high demand alterative, with reasonable computational requirements, they will have achieved readiness level 4.

Next, panel members began examining the level 5 criteria in order to guide recommendations for the project team. One question was raised about the external and internal system interfaces, and whether the Python code's individual components and their functionalities were modular. Modular components would facilitate research on particular components of the model, such as the pathfinder. Other teams may be working on similar problems and could be interested in testing their algorithms within the Fast-Trips framework – an opportunity for widened research collaboration.

A target operational requirement for runtime was later given by the team to be 5 to 8 hours per global iteration, which is the SFCTA's current model's runtime. The panel noted that the team did not discuss convergence to a great extent in their presentation, and it hasn't been defined yet. The panel acknowledged that it is a given that tighter integration and faster runtime will always be a goal in these types of projects, so future work to achieve readiness level 5 would be to consider what reasonable targets should be and formalize the operational requirements (convergence and runtime), e.g., what convergence is need for an application.

Panel recommendations for advancing the Fast-Trips Dynamic Transit Passenger Assignment (DPA) include:

1. Prepare guidelines for others on Dynamic Transit Passenger Assignment.
2. Identify specific applications and develop application-specific runtime and convergence requirements.
3. Prepare the model for use as a research and teaching tool.
4. Enhance the modularity of the software code.
5. Continue efforts to address runtime issues
6. Consider the possible homes for the tool at the end of the project.

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