MD-18-SP709B4K

MARYLAND DEPARTMENT OF TRANSPORTATION STATE HIGHWAY ADMINISTRATION

RESEARCH REPORT

ANALYZING TRAVELERS' RESPONSE TO DIFFERENT ACTIVE TRAFFIC MANAGEMENT (ATM) TECHNOLOGIES

CHENFENG XIONG, LEI ZHANG, KATHLEEN STEWART
JUNCHUAN FAN, MINHA LEE, WEIYI ZHOU

Maryland Transportation Institute (MTI)

University of Maryland

FINAL REPORT

August 2018

The contents of this report reflect the views of the author who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Maryland Department of Transportation. This report does not constitute a standard, specification, or regulation.

Technical Report Documentation Page

1. Report No. SHA/UM/4-40	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Analyzing Travelers' Response to Different Active Traffic Management (ATM) Technologies		5. Report Date August 2018 6. Performing Organization Code	
7. Author/s Chenfeng Xiong, Ph.D. Assistant Research Professor Lei Zhang, Ph.D. Herbert Rabin Distinguished Professor Kathleen Stewart, Ph.D. Professor Junchuan Fan, Ph.D. Research Scientist Minha Lee, Graduate Research Assistant Weiyi Zhou, Graduate Research Assistant		8. Performing Organization Report No.	
9. Performing Organization Name and Address Maryland Transportation Institute (MTI) University of Maryland College Park, MD, 20742		10. Work Unit No. (TRAIS) 11. Contract or Grant No. SP709B4K	
12. Sponsoring Organization Name and Address Maryland State Highway Administration Office of Policy & Research 707 North Calvert Street Baltimore MD 21202		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code (7120) STMD - MDOT/SHA	
15. Supplementary Notes			
16. Abstract Maryland Department of Transportation State Highway Administration (MDOT SHA) is investigating innovative solutions to improve mobility with the help of the Active Traffic Management (ATM) technologies. Developing appropriate modeling and simulation tools with the capability of analyzing traffic pattern, travel demand, and traveling/driving behavior responses along the most critical corridors in Maryland are the prerequisite to implementing any ATM strategies. During the past ten years, MDOT SHA has successfully developed several effective modeling tools for traffic operations, dynamic traffic simulation, planning analysis, and travel demand forecasting, in collaboration with the University of Maryland. The Coordinated Highway Action Response Team (CHART) at MDOT SHA has integrated dynamic traffic monitoring, traveler information, weather information, and agency updates into their real-time operations and incident/emergency responses. In this project, the Maryland Transportation Institute (MTI) research team has developed an integrated travel behavior and dynamic traffic assignment modeling tool and adapted the tool for real-time and dynamic analysis of active traffic management (ATM) strategies. The model is fully calibrated and validated using disaggregated data collected in the base year of 2015, including hourly traffic counts, corridor-level travel times aggregated in 15-minute intervals, individual vehicle trajectories, and energy consumption at the trip-level. A series of performance measures has been developed and employed to assess the effectiveness of each ATM strategy and evaluate the combined effect. Travel behavioral responses are also modeled and measured, including the departure time responses and the driving behavior.			
17. Key Words Active Traffic Management; Ramp Metering; Variable Speed Limit; Mesoscopic Model; Travel Behavior	18. Distribution Statement: No restrictions This document is available from the Research Division upon request.		
19. Security Classification (of this report) None	20. Security Classification (of this page) None	21. No. Of Pages 37	22. Price

Form DOT F 1700.7 (8-72) Reproduction of form and completed page is authorized.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

ATM	Active Traffic Management
TSM&O	Transportation Systems Management & Operations
CHART	Coordinated Highway Action Response Team
DTALite	A light-weight dynamic traffic assignment and simulation engine
AgBM-DTALite	The integrated model of agent-based travel behavior and DTALite dynamic traffic assignment
VSL	Variable Speed Limit
BUE	Behavioral User Equilibrium
ALINEA	The name of an adaptive ramp metering control algorithm
ALINEA-Q	An alternated ALINEA with consideration of ramp queue lengths
MOVES	Motor Vehicle Emissions Simulator
MOVESLite	A light-weight simulator of MOVES
MSTM	Maryland Statewide Transportation Model
RITIS	Regional Integrated Transportation Information System
WMSE	Weighted mean squared error

EXECUTIVE SUMMARY

Maryland Department of Transportation State Highway Administration (MDOT SHA) is investigating innovative solutions to improve mobility with the help of the Active Traffic Management (ATM) technologies. Developing appropriate modeling and simulation tools with the capability of analyzing traffic pattern, travel demand, and traveling/driving behavior responses along the most critical corridors in Maryland are the prerequisite to implementing any ATM strategies. During the past ten years, MDOT SHA has successfully developed several effective modeling tools for traffic operations, dynamic traffic simulation, planning analysis, and travel demand forecasting, in collaboration with the University of Maryland. The Coordinated Highway Action Response Team (CHART) at MDOT SHA has integrated dynamic traffic monitoring, traveler information, weather information, and agency updates into their real-time operations and incident/emergency responses. These existing modeling tools and data infrastructures have paved a solid foundation for modeling development that is suitable for ATM analysis and real-time Transportation Systems Management and Operations (TSM&O).

In this project, the Maryland Transportation Institute (MTI) research team has developed an integrated travel behavior and dynamic traffic assignment modeling tool at the mesoscopic level, the AgBM-DTALite, and adapted the tool for real-time and dynamic analysis of active traffic management (ATM) strategies. The model is fully calibrated and validated using disaggregated data collected in the base year of 2015, including hourly traffic counts, corridor-level travel times aggregated in 15-minute intervals, individual vehicle trajectories, and energy consumption at the trip-level. Then the model is applied to evaluate several proposed ATM strategies on the I-270 corridor, including Variable Speed Limit (VSL), dynamic ramp metering controls, as well as various roadway improvements (lane addition, extension of acceleration and deceleration lanes etc.). A series of performance measures has been developed and employed to assess the effectiveness of each ATM strategy and evaluate the combined effect. Travel behavioral responses are also modeled and measured, including the departure time responses and the driving behavior.

The major innovations in this ATM research are three-fold:

- The travel behavioral models are tightly integrated in the simulation of ATM, allowing the model to assess different aspects of behavioral responses to the ATM strategies.
- The AgBM-DTALite integration and its embedded Behavioral User Equilibrium (BUE) greatly improves the computational efficiency of the mesoscopic simulation, which grants the capability of large-scale applications, as well as the high resolution at the minute-by-minute level.
- The minute-by-minute tight integration of ATM algorithms in the AgBM-DTALite is an innovation. With this, mesoscopic models can be adopted to evaluate real-time transportation systems management and operations.

With these research innovations, the team has applied the AgBM-DTALite to evaluate I-270 innovative transportation management ATM strategies. By applying the modeling tool, significant departure time behavioral changes are found in response to ATM and the subsequent changes in traffic conditions. At the aggregate level, a “peak concentration” phenomenon is identified in the AM peak. Due to the mitigated peak congestion, current travelers are more

willing to switch back to peak-hour departure times to avoid too early or late schedule. The side effect will be the slightly increased peak travel times, compared to the conditions where travelers' departure time patterns are fixed. Modal shifts and route changes are found much less significant. This behavioral sensitivity will certainly play an important role in current and future ATM and TSM&O analyses, as travel behavioral patterns are being reshaped and will influence the traffic conditions and decision-making in return. The team has also developed a Python-based analytical toolbox to evaluate driving behavior and its spatial-temporal (space-time) interrelationship with traffic and incidents.

1. INTRODUCTION

Active traffic management (ATM) is a pro-active approach to corridor traffic operations and has the potential to allow the Maryland Department of Transportation State Highway Administration (MDOT SHA) to better manage the increasing travel demand and improve the travel reliability. ATM technologies may better utilize the capacity or provide additional capacity to accommodate peak-hour traffic, improve the detection and response to incidents, reduce delays resulted from recurrent congestion and/or incidents, and thus enhance the transportation network's performance in safety, efficiency, reliability, and sustainability.

Currently, an increasing number of ATM strategies are deployed or being evaluated across the country. For instance, adaptive ramp metering is operational in Los Angeles, CA, Minneapolis, MN, Portland, OR and Houston, TX (PB and UMD, 2014). Dynamic speed limits are adopted in Mobile County, AL, Flagstaff AZ, Pittsburgh, PA, Texas, and Northern Virginia (Nezamuddin, et al. 2011; PB and UMD, 2014; Asare and Smith, 2014). Dynamic lane control strategies are seen in Virginia and Washington State (PB et al., 2007; Francis, 2013). The expected benefits of ATM include: (1) More efficient and reliable passenger and freight movements; (2) Increased corridor mobility and safety; (3) Revenue generation and cost-effective way of enhancing throughput; (4) Decreased fuel consumption and environmental benefits. Issues of ATM on operations and safety (e.g. distracted driver attention and inevitable lane drop at the end of the shoulder-use section) are also discussed in several studies.

MDOT SHA has long been a pioneer in traffic system management and operations. The multi-jurisdictional Coordinated Highway Action Response Team (CHART) has integrated live traffic monitoring, traveler information, severe weather information, and agency updates into their real-time operations and incident/emergency response and management. Several active traffic management strategies are applied, tested, and/or planned in Maryland. For example, dynamic message signs are deployed on several corridors including the I-95 corridor and I-495 corridor to convey traveler information and queue warning. Designated high-occupancy vehicle lanes and electronic toll lanes (ETL) are used in the busiest freeway segments such as I-270 and I-95, to manage excessive travel demand, especially during the peak hours. With the rapidly growing travel demand in the region, D.C.-Baltimore metropolitan areas are constantly ranked at the top of the list of the most congested cities in the U.S. Innovative solutions, such as the ATM strategies, may provide promising and cost-effective ways to improve mobility. A few notable ATM examples in the greater Washington D.C. area include the ramp metering control implemented on I-395, variable speed limits on I-66, and dynamic tolling on I-495 ETL. MDOT SHA has also begun investigating these innovative solutions. Currently, the application of the ramp metering control strategy is in the planning stage, among a few other strategies.

To facilitate the evaluation of ATM, this project deployed an innovative modeling framework that tightly integrates travel behavior, dynamic traffic assignment, and ATM control algorithms. The model was applied to the D.C.-Baltimore regional network. Ramp metering, variable speed limit, and a few geometry changes proposed for the I-270 corridor have been evaluated using the modeling tool. In addition, the project has collected vehicle fleet data to evaluate driving behavior and its spatiotemporal (space-time) interrelationship with traffic and incidents.

2. LITERATURE REVIEW

The team has conducted a comprehensive literature review and delivered the report as the first deliverable of this project. We have reviewed a few signature ATM strategies: 1) ramp metering control; 2) variable speed limit and queue warning; 3) hard-shoulder running; 4) work zone management, and 5) Toll pricing. The scan of practices reviewed detailed information on the applications of the selected ATM strategies, including the methodologies, projected/actual impacts, and limitations of the reviewed practices.

The first major finding from the literature review was that most of the reviewed studies were solely simulation-based and did not have or only have limited travel behavioral representations. This may potentially lead to bias. The introduction of ATM controls may encourage certain behavioral shifts in different behavioral dimensions. Taking ramp metering as an example, the improved freeway traffic and the additional delay at the metered ramps may influence the departure time choices of the freeway and ramp users. The formation of new travel behavior patterns was certainly a critical aspect of accurate Analysis, Modeling, and Simulation (AMS).

Another finding from the literature review was that the reviewed practices mostly focus on a single ATM control strategy. In real-world situations, it is often the case that multiple controls are implemented on a corridor to work coordinately in alleviating congestion. For instance, ramp metering control and variable speed limits may be deployed together on a busy corridor (e.g. I-270, I-95) to maximize the movement of under recurrent and/or non-recurrent congestion. The compound effects from both controls should not be omitted. The coordinated control strategy design can be an advanced research topic for the research team to explore when conducting the AMS analysis of the ATM controls.

The research gap is the lack of proper travel behavioral models and data. To fill the gap, the research team employed and further developed the integrated AgBM-DTALite modeling system (i.e. an integrated model of Agent-based Behavioral Model and DTALite traffic simulation) for the modeling and evaluation of ATM strategies (Zhang et al., 2014; Xiong et al., 2016). The behavioral module, the AgBM, considers the full-fledged travel behavioral dimensions, including the departure time choice, route choice, travel mode choice, and en-route diversion choice, which augments the capability of dynamic traffic assignment (DTA) and mesoscopic traffic simulation models to capture both traffic impact and travelers' behavior responses to ATM.

The literature review also provided evidence for the development of the ATM algorithms. Various ramp metering and variable speed limit (VSL) implementations in the U.S. were reviewed to design the algorithm employed in this project (See Table 1 and Table 2). The speed logic, VSL control time interval, and the length of the controlled segments were important decision variables in the algorithm (Riffkin et al. 2008; Waller et al., 2009; Lyles et al., 2004; Allaby et al., 2007; Lee et al., 2004). Heuristics and optimizations are the two popular approaches to obtaining VSL solutions (e.g. Yang et al. 2013; Zegeye et al., 2010). The state-of-the-practice was reviewed and used in the implementation of VSL in our models.

Table 1. Examples of Ramp Metering Applications in U.S.

State	Location	Size	Type	Impacts
Minnesota	I-494, I-94, I-35W and I-35E in Twin Cities	431 ramp meters	Mostly centralized control and a few ramps are fixed; operation hours vary	Travel time decreased by 22%; crashes increased by 26%; and 2.3 minutes of delay on average for vehicles on ramps
Texas	TX 360 in Arlington	5 ramp meters	Local pre-timed control with a 4-second cycle during the morning peak period of 6:15 – 8:30 AM	Travel time decreased by 10%
	I-10, I-45, I-610, US 59, US 290, and TX 225 in Houston	Less than 50 ramp meters	Fixed control during morning peak of 6:30-9:30 AM and evening peak of 3:30-6:00 PM	Travel time decreased by 22% and speed increased by 29%
North Carolina	Westbound I-540 in north Raleigh	4 ramp meters	Expected to be operational by September 2017	-
Georgia	I-20, I-285, I-575, I-75, I-75/85 connector, I-85, Buford connector, GA 400, US 78 in Atlanta	185 ramp meters as of 2011 and added over 200 ramp meters since then	Fixed meter and the operation hours vary depending on the ramp location and the main highway conditions	10% decrease in travel time; benefits are four times greater than the cost after one year and 20 times greater after five years
Washington	I-5, SR 520, I-90, I-405, and SR 167 in many locations including Seattle; more meters are under construction	More than 100 ramp meters	Centralized control during morning peak of 6:30-9:00 AM and evening peak of 3-7 PM	Collisions reduced by at least 30%; travel time decreased 3 to 16 minutes on I-405 in Renton
Kansas and Missouri	South I-435 between Metcalf Avenue and the Three Trails Memorial Crossing in Kansas City, and the US 69 and 135th Street Interchange in Overland Park	8 ramp meters	The controls are active when pavement sensors detect traffic congestion on Monday through Friday during morning and evening peak hours	Overall accidents decreased by 64%; cutting accidents decreased by 81%
California	Among 12 District in California, every district has ramp metering installed or planned except District 1 and 9.	2,954 ramp meters as of December 2015	While operation time varies in each District with adaptive controls, District 7 including Los Angeles has largest number of controls, 1025 in operation and 192 more planned followed by District 4 including San Francisco, 708 exist and 637 planned.	Crashes decreased by 50% while the traffic throughput increased by 3 to 5% in District 3; In District 7, speed improved 15 mph, and fuel consumption decreased by 13%
Virginia	I-395 and I-66 as part of the Integrated Corridor Management program	18 metered ramps on I-395 and 8 on I-66	Operation time varies with adaptive metering controls based on traffic conditions	-
Oregon	I-205, I-405, I-84, I-5, US 26 and Route 217, in the Portland metro area	More than 140 meters	Ramp meters rely on freeway traffic volumes while operation time varies	155% travel speed increase, 43% crash decrease; 700 gallons of fuel per weekday saved

[1] *Sources: State department of transportation websites listed in references (e.g. MNDOT, 2001; TTI, 2001; Kansas and Missouri DOT, 2011)*

Table 2. Examples of VSL, DMS and Queue Warning Applications in U.S.

State	Status	Location	Size	Speed Logic
Arizona[1]	Experimental	Simulation test on I-40	NA	Fuzzy logic based on road surface condition, wind speed, visibility, precipitation
Colorado[1]	Active	Rural - Eisenhower Tunnel on I-70 west of Denver	Inside the Eisenhower Tunnel	Computing a safe speed based on the truck weight, speed, and axle configuration
Michigan[1]	Active during 1962 – 1967; currently inactive	Urban – M-10 (John C. Lodge Freeway) in Detroit between the Edsel Ford Freeway (I-94) and the Davison Freeway	5.2 km with 21 variable speed signs	The speed limit manually switched at the control center in increments of 5-mph from 20 to 60 mph based on CCTV and freeway speed
Minnesota[1]	Demonstration	Urban (variable)	Variable based on the size of work zone	With the presence of construction worker: 65 mph; otherwise a designated worker changes to 45 mph
Nevada[1]	Active	Rural – on I-80 next to a coal-fired power generation facility in a canyon with a river	Two VSL for each direction with flashing-type warning signs	A logic tree based on the 85th percentile speed, visibility, road surface conditions with increments of 10-mph
New Jersey[1]	Active	Urban/Rural – New Jersey Turnpike	120 signs over 148 miles	Posted speed limits are based on average travel speed and reduced to 30 mph with increments of 5-mph
New Mexico[1]	Active during 1989 – 1997; currently inactive	Urban – I-40 eastbound in Albuquerque	3 VSL sings in 3 miles	Summation of smoothed average speed and environmental condition constant with the range of 30 to 55 mph; minimum speed limit is also displayed
Washington[1]	Active	Rural I-90 Snoqualmie Pass	13 VMS over 40 miles; VSL operated in 17 miles during the winter season	65 mph is posted limit and reduction is based on feedback from traffic condition matrix, weather stations, snow plow operators, and State Patrol in 10-mph increments
Virginia[2]	Active in year 2008	I-495 Outer Loop from Springfield Interchange to between the Telegraph Road and US 1 Interchanges; Inner Loop from the midpoint of the Woodrow Wilson Memorial Bridge (WWB) to the Eisenhower Avenue Connector Interchange	7 VSL signs on the Outer Loop and 5 on the Inner Loop; DMS and warning signs before the VSL zone	Posted limit is 55 mph; VSL activated with a lane closure; the maximum is 50 mph and the minimum is 35 mph by VSL
Virginia[3]	Active in year 2016	I-77 in Carroll County between mile markers 0 and 15	76 signs of various alert types	Based on visibility and road conditions, the speed limits vary between 65 and 30 mph.

[1] *Sources: Robinson, M., Examples of Variable Speed Limit Applications, 2000*

[2] *Sources: Fudala, N.J. and M.D. Fortaine, Work Zone Variable Speed Limit Systems: Effectiveness and System Design Issues, 2010*

[3] *Sources: Retrieved from VDOT website: http://www.virginiadot.org/newsroom/salem/2016/vdot_launches_new_variable109320.asp*

In terms of ramp metering algorithms, the team reviewed and compared the pros and cons of fixed-rate ramp metering, local traffic-responsive ramp metering, and coordinated ramp metering. It was found that the coordinated metering was not vastly superior, especially since it is more expensive and complicated to implement and operate. The effects of the coordinated metering are known to be sensitive in terms of the values of the parameters (Zhu et al. 2011; Ahn et al., 2012; Chu et al., 2005). In this regard, adaptive algorithms that are local-traffic responsive, such as ALINEA and ALINEA-Q (an alternated ALINEA with consideration of queue lengths on the ramp), are believed to be robust and perform with competent effectiveness.

These major findings from the literature review have paved the foundation for our simulation, modeling, and analysis. Interested readers can go to our other project deliverable: Report on Literature Review, for more information. In the following sections, we will explain our modeling methodology, data, calibration, and validation in detail.

3. INTEGRATED MESOSCOPIC MODELING METHODOLOGY

3.1. The Integrated Mesoscopic Modeling Framework

The AgBM-DTALite framework is well-suited for the modeling and evaluation of active traffic management strategies, including dynamic ramp metering and variable speed limit control (Xiong et al., 2018). The AgBM-DTALite framework was revised to incorporate the real-time ATM control (as shown in Figure 1).

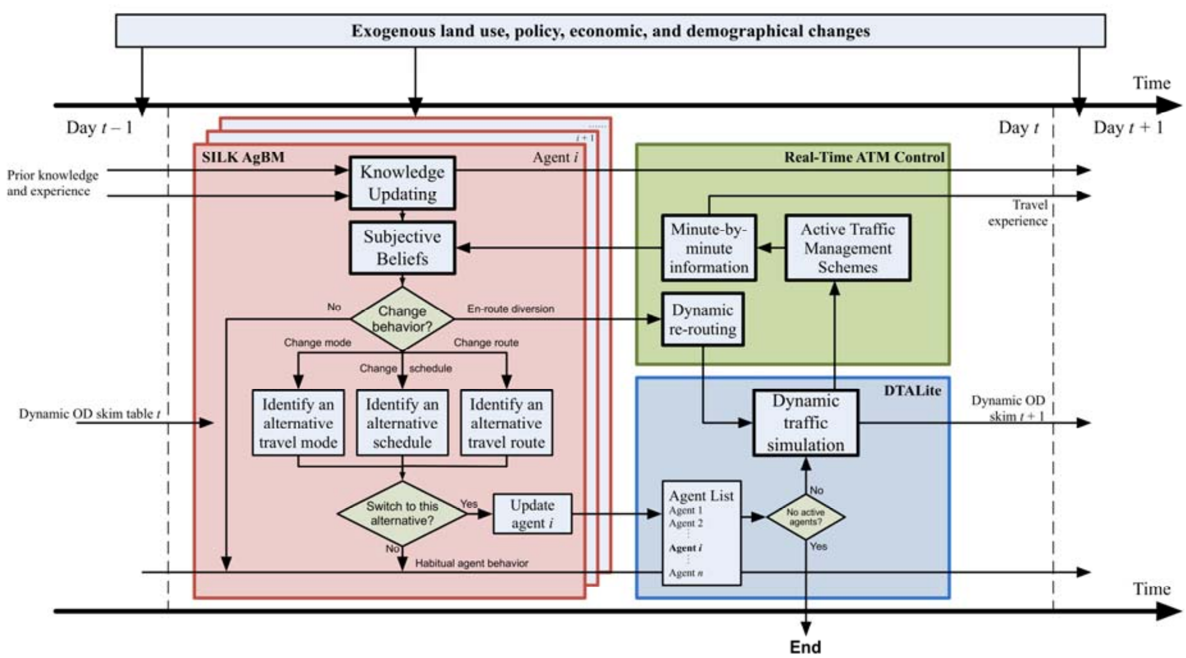


Figure 1. The integrated model of AgBM and DTALite for real-time active traffic management (ATM) control

The key features are highlighted as follows:

- The DTALite module (i.e. an open-source Light-weight Dynamic Traffic Assignment and Simulation Engine, https://code.google.com/p/nexta/) is capable of simulating ATM strategies by controlling the link attributes in a time-dependent manner (Zhou and Taylor, 2014). In addition, it simulates traffic dynamics in greater detail and estimates various time-dependent traffic conditions such as volume, density, etc. In a simulation environment, these pieces of information in a minute-by-minute setting are critical in modeling/controlling ramp metering rates and variable speed limits dynamically.
- Behavioral responses in departure time and route adjustments can be modeled and assessed. Within the same simulation day, traffic information is conveyed between AgBM and DTALite. Agents who possess real-time information could react to the ATM when driving on the road (Xiong and Zhang, 2013). This en-route diversion is incorporated in this integrated model. Between simulation days, agents arrange their daily or recreational itinerary based on knowledge and various information sources: previous experience, social network, mass media, real-time traffic data sources (e.g. Google, WAZE and INRIX), etc. Exogenous changes, such as the implementation of ATM, may result in a different adjustment to the travel itinerary. AgBM models the travel behavior with the full consideration of search, information, learning, and knowledge. An agent's travel experience, under the influence of ATM, will inform and update her/his own knowledge and alter her/his subjective beliefs/expectations about travel conditions. A higher expected gain compared to the search cost (modeled as the mental/physical effort spent on searching) will lead to behavioral adjustments.
- A Behavioral User Equilibrium (BUE, where all users stop seeking behavioral changes) is developed to guide the model convergence process. When applied to ATM analysis, the existence of BUE indicates that travelers will only search and adjust their behavior in limited times when responding and adapting to the ATM strategies. Compared to traditional User Equilibrium or dynamic traffic assignment, this BUE process incorporates more behavioral dimensions (route choice, departure time, and travel mode choice) and is guaranteed to converge.

The base network was extracted from a regional activity-based model, InSITE, developed and maintained by Baltimore Metropolitan Council (BMC), and the Maryland Statewide Transportation Model (MSTM), developed and maintained by MDOT SHA. The extraction involved the traffic supply (geographic information) and the travel demand (Origin-Destination tables, or OD tables). The travel demand, including the OD and the behavioral models, was first calibrated by observed traffic data in the base year for a status-quo scenario. The output file, recording each agent's departure time, route choice, and arrival time, became the input file for the integrated AgBM-DTALite model. In the after scenario with ATM, agents could find that their current travel behaviors, like departure time and route choice, were no longer optimal and need adjustments. In this step, the team defined search gain and search cost for agents to determine if they would make any change. To better simulate travelers in the real world, the team also included subjective beliefs in the evaluation process, which assumed not all the travelers have perfect information. After all the agents stop switching departure time or route choice, i.e. none of them could get more search gain than search cost, a new user-equilibrium network was reached and was then ready to compare to the before scenario without ATM applications.

Applying the BUE and AgBM-DTALite, a major advantage is the embedded behavioral foundation. The calibrated behavioral models, especially the rule-based departure time choice model in the AgBM, the typically static OD extracted from InSITE/MSTM, were modeled and converted to a truly dynamic OD demand. Conventional transportation planning models usually implement hourly or time-of-day OD tables. As shown by the gray curve in Figure 2, the seed OD used by the model has a universal departure rate during the AM Peak hours (6 AM - 9 AM). After the BUE convergence is reached, the departure time patterns were more dynamic and more realistic (calibration/validation results will be shown in the next subsection). Getting an accurate departure time profile of the travelers was crucial to the analysis of ATM strategies, as departure time changes of individual travelers were the most significant behavioral adjustment in response to those highly dynamic interventions.

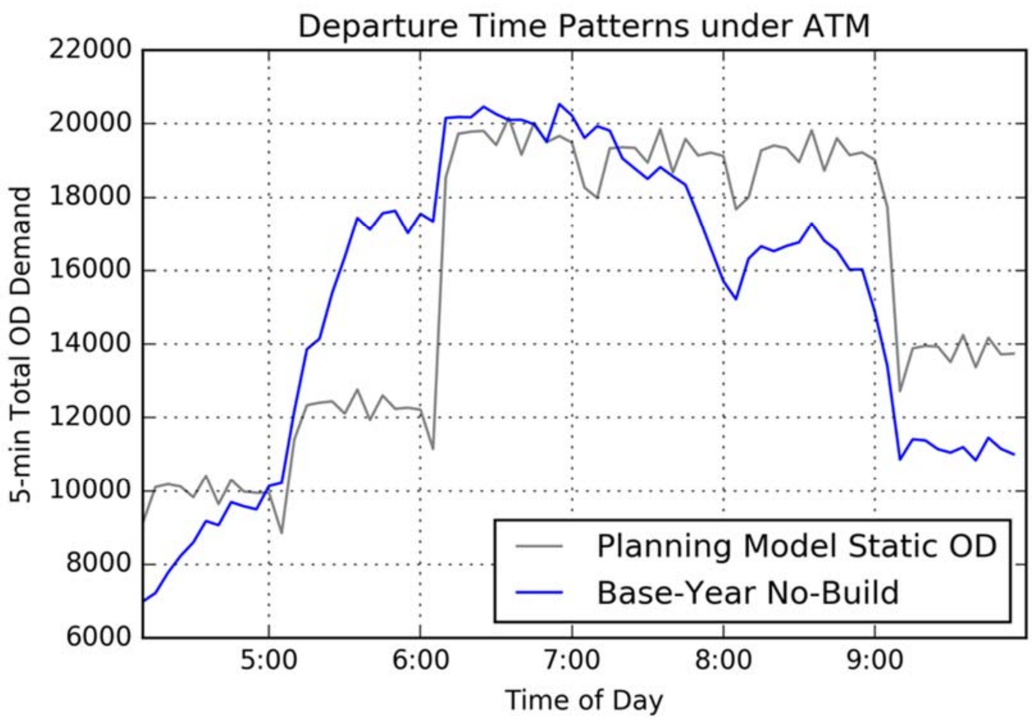


Figure 2. The dynamic OD pattern modeled by the AgBM-DTALite model

3.2. Model Calibration and Validation

Figure 3 illustrates a systematic framework of the calibration and validation of the integrated mesoscopic model. The core of the system model is the integrated AgBM-DTALite model, which simulates agent behavior, traffic trajectories, and energy consumption in a time-dependent way. AgBM-DTALite adopts an integrated offline calibration model to adjust all its internal model parameters based on historical observations. The outputs are used for model validation against real-time data feeds, including fixed traffic flow detectors and probe vehicle sensors. Finally, model sensitivity was analyzed through scenario analysis.

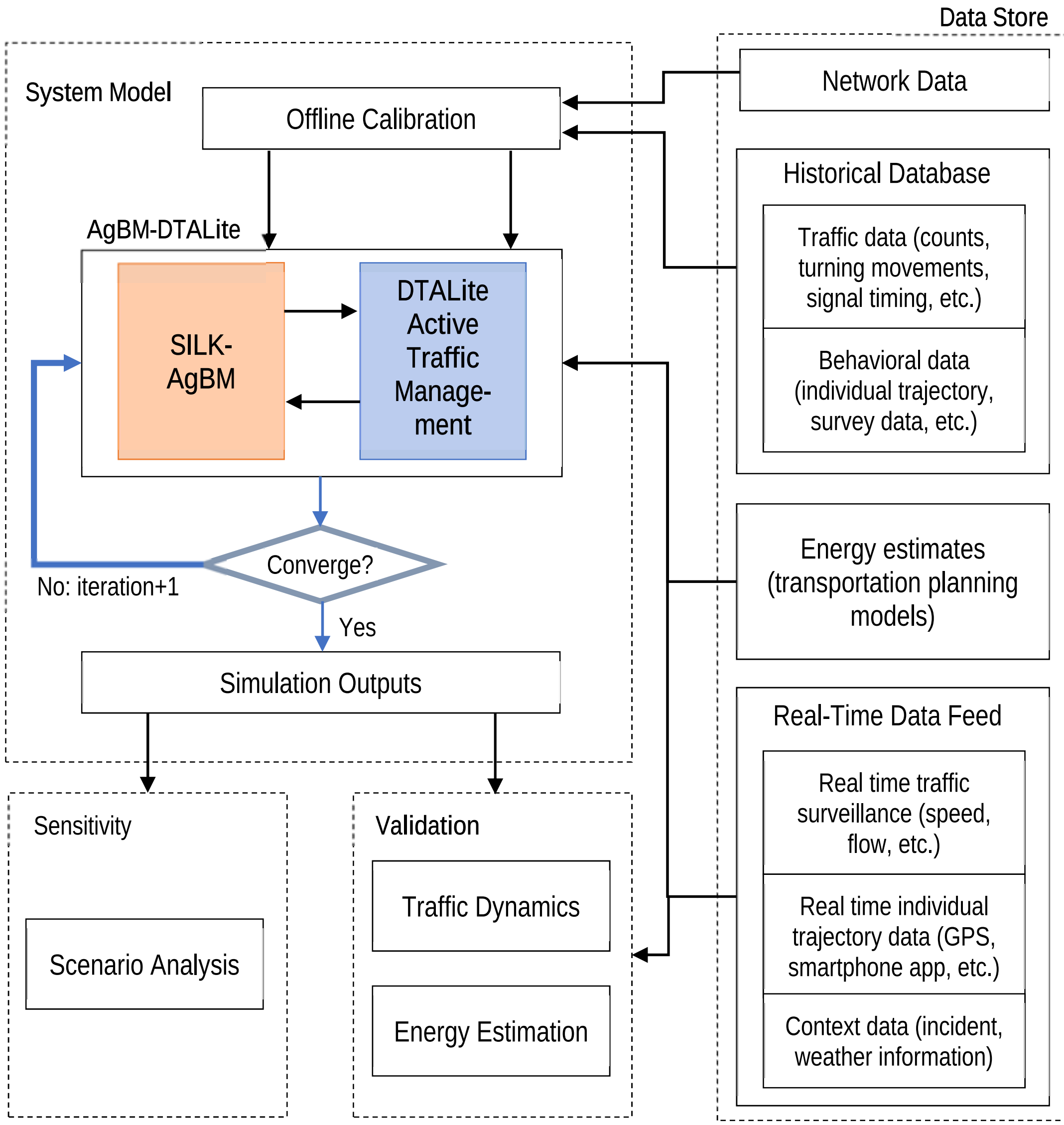


Figure 3. A systematic framework of the calibration, validation, and sensitivity analysis

A two-stage offline calibration approach was adopted in the integrated model. In the first stage, OD matrices were calibrated using an iterative path-based OD adjustment algorithm. In the second stage, supply-side link level parameters were adjusted using calibration and validation of link-level speeds. The testing and validation process of the model included two aspects: 1) validation of corridor travel times based on probe vehicle data; and 2) validation of energy consumption based on vehicle-level energy measurements. The vehicle-level trajectories, second-by-second vehicle-level energy, and speed in the data store supported this testing and validation.

The model covered the entire region of Washington, D.C.; Montgomery, Prince George's and Frederick Counties in Maryland, as well as parts of Baltimore County; and Arlington and Fairfax

Counties in Virginia. All the geographic information and traffic infrastructure information of this network came from the Maryland Statewide Transportation Model (MSTM). The network (shown in Figure 4) contains 1,228 traffic analysis zones, 16,563 nodes, and 42,240 links. All the interstate freeways, highways, most of the major and minor arterials, and some of the connectors and local roadways are included in this network. The DTA model is coded in the light-weight, open source software package, DTALite. The research team chose DTALite because its built-in parallel computing capability dramatically speeds up the traffic assignment and OD estimation process when using multi-core CPU hardware.

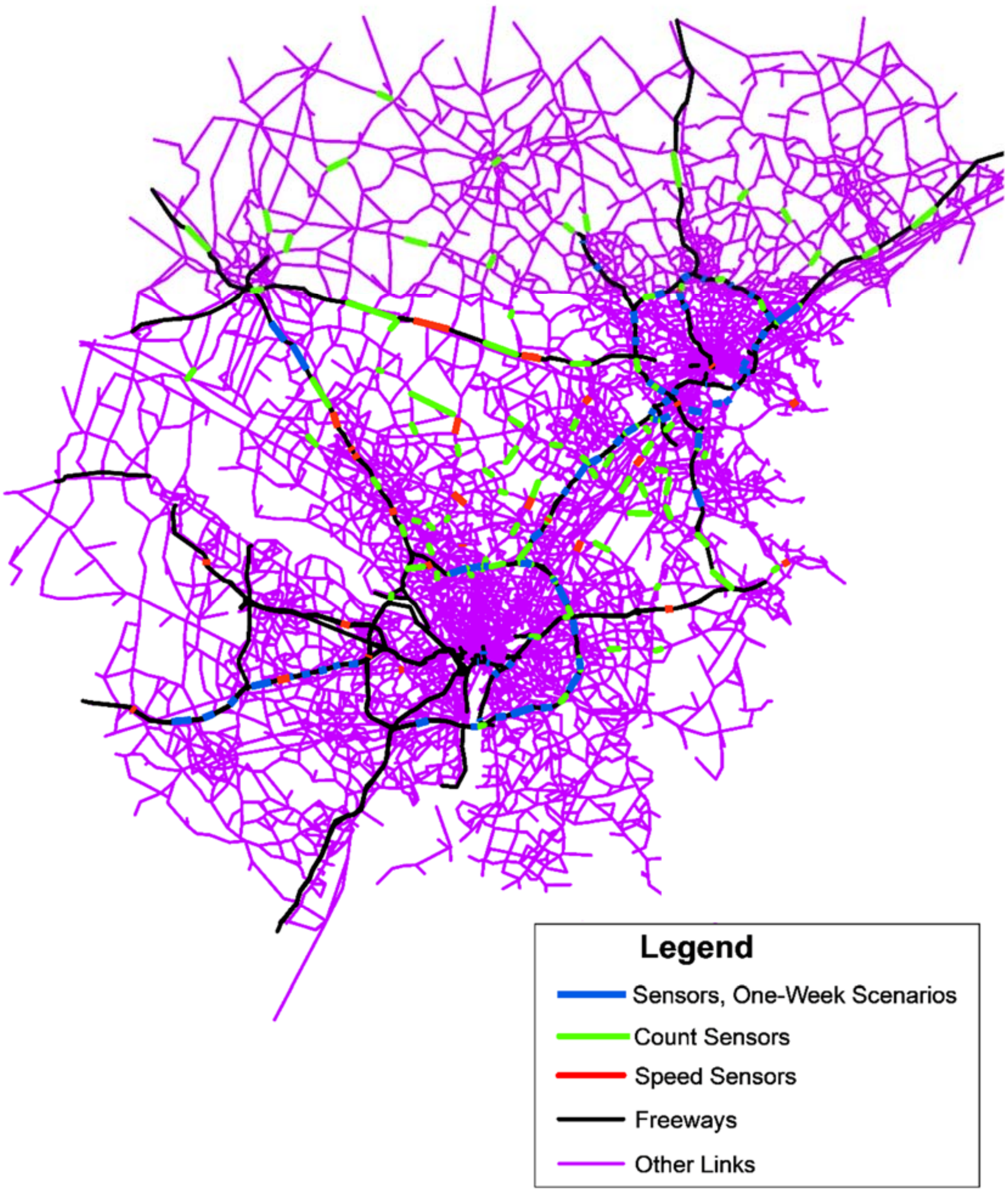


Figure 4. The mesoscopic modeling network and locations of the count and speed sensors

The traffic dynamic model (i.e. DTALite) was calibrated for a 24-hour basis, for six representative day scenarios: Monday, Tuesday, Wednesday, Thursday, Friday, and weekend (defined for a typical week). The data collection effort fetched traffic count data for Tuesdays, Wednesdays, and Thursdays (184 counting stations marked by green in Figure 4, source: MDOT SHA i-TMS system), additional count data for each day of the week (128 counting segments marked by blue in Figure 4, source: the Level-2 statewide transportation network developed by MDOT SHA), and speed sensor data (60 speed sensors filtered by data reliability marked by red in Figure 4, source: Regional Integrated Transportation Information System, RITIS). All the data has been collected in the year of 2015 for data consistency.

The seed OD tables came from the MSTM model, all of which are divided into hourly volume from time interval 00:00-01:00 to time interval 23:00-24:00. In the DTALite, the team utilized the OD matrix estimation (ODME) procedure to first perform traffic assignment to achieve user equilibrium (UE), then adjusted the OD tables based on the UE route choices. For the volume calibration, the team used the weighted mean squared error (WMSE) to calculate the difference between simulation results and the observed traffic counts:

$$WMSE = \sqrt{\frac{\sum_{i=1}^{N}\sum_{t=1}^{T}(\mathrm{y}_{i,t}^{*} - \mathrm{y}_{i,t})^2}{\sum_{i=1}^{N}\sum_{t=1}^{T}\mathrm{y}_{i,t}^{2}}} \qquad (1)$$

where $y_{i,t}$ and $y_{i,t}^{*}$ denote the observed and simulated traffic volume (or speed), respectively, at each link i during time interval t, N denotes the total number of sensors, and T denotes the total number of time intervals.

Travel time validation was also important for predictions and result visualizations. The output files of DTALite provided average travel time for different links during different time periods. The validation data was obtained from the RITIS website (www.ritis.org). The team collected historical data on different freeway/highway segments for all of 2015 based on the traffic message channel (TMC) code; both travel time and travel speed were included in the data set. The links selected for travel time validation are the ones highlighted in Figure 5. A total of 552 road segments on 23 freeways were selected in the RITIS website for this validation. After obtaining the data, the team summarized the average hourly travel time on each road segment for different hours of the day and validated the model by calculating WMSE with respect to simulation outputs.

A commonly used emissions estimation model called “Motor Vehicle Emissions Simulator” (MOVES) was integrated into the AgBM-DTALite; this adapted package is called MOVESLite. In addition to validating the corridor-level travel times, the validation of the integrated model also validated the energy estimator at the vehicle trip level. MOVESLite estimates the energy and emissions for each trip based on vehicle type, vehicle age, and Operation Mode (OpModeID) of the vehicle during the model running process. Energy consumption estimation in DTALite is controlled via three inputs: “input cycle emission rates”, “input emission rates” and “optional vehicle emission rates”. This energy consumption estimation was validated against true vehicle energy consumption data collected based on a naturalistic driving fleet deployed in the D.C.-Baltimore area. The energy consumption data was collected by a small on-board unit (OBU) device. While energy consumption estimation was not a central focus of this project, it enabled the potential applications of the model to evaluate emissions, air quality, environmental impacts, and vehicle-level energy usage of the transportation system, making the integrated model a comprehensive AMS tool. The calibration and validation results are summarized and reported together in Table 3.

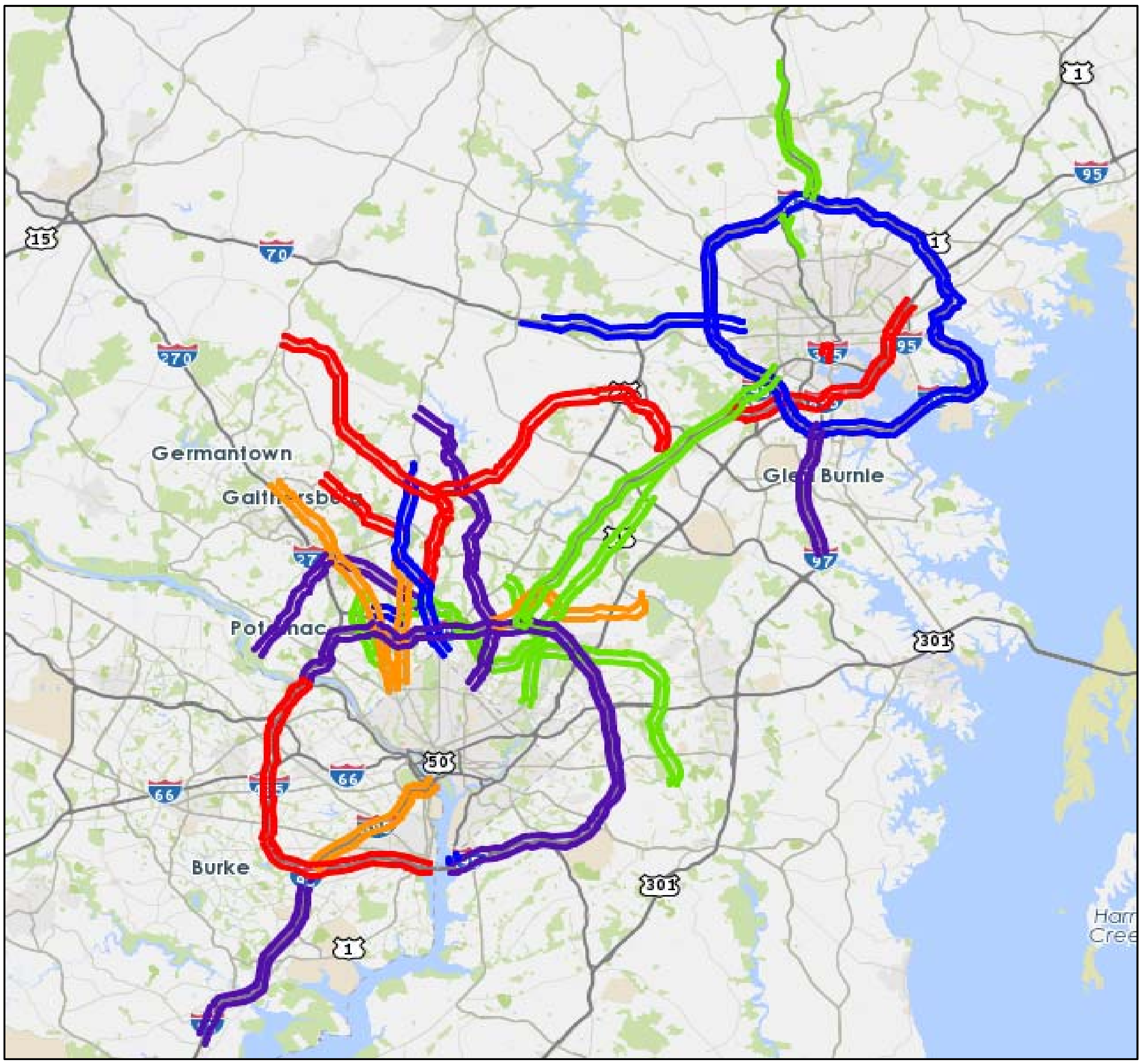


Figure 5. Selected freeway and arterial roadway segments for travel time validation

The research team summarized the calibration and validation work done in developing the integrated model in Table 3. The computing time, count error before and after calibration, travel time validation, and vehicle energy validation are summarized for each of the six scenarios.

Table 3. The Calibration and Validation Summary

Scenario Name	Rounds of Calibration	CPU Hours Spent on Calibration and Validation	Count Error Before Calibration	Count Error After Calibration	Travel Time Validation	Vehicle Energy Validation
Monday	17	204	38.50%	14.45%	18.9%	16.2%
Tuesday	15	180	36.72%	14.59%	18.8%	17.4%
Wednesday	15	180	33.66%	13.78%	19.0%	15.9%
Thursday	26	312	35.88%	13.36%	18.9%	15.0%
Friday	24	288	39.09%	14.47%	18.9%	14.9%
Weekend	29	348	44.90%	13.96%	15.7%	14.1%

3.3. Active Traffic Management Algorithms

The key challenge of implementing the ATM and real-time TSM&O in the integrated AgBM-DTALite system was the input-output interaction between the integrated model and the control algorithms. To achieve a truly dynamic control, traffic dynamics including link density, queue, volume weare generated from the simulator and then extracted to the control algorithms. In return, link ramp metering rates and updated speed limits were generated and exchanged into the simulator. This data exchange was completed at the minute-by-minute level. Detailed ATM integration and algorithms are illustrated in Figure 6.

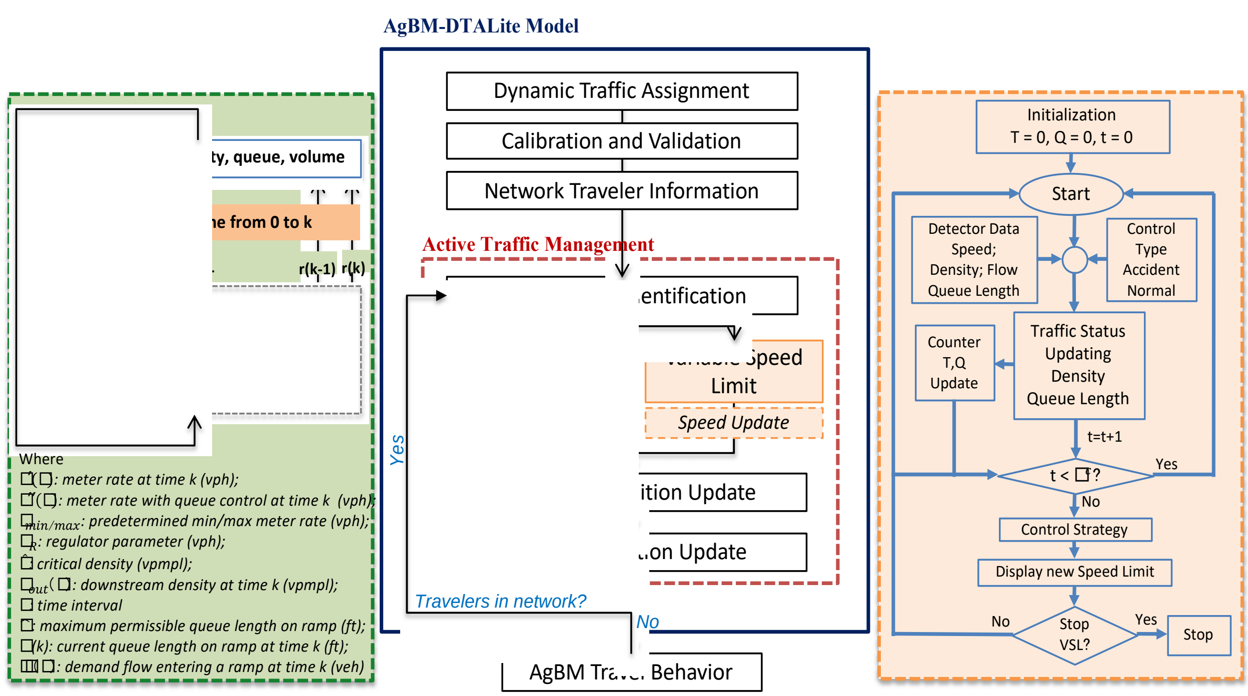


Figure 6. The tight integration for active traffic management using AgBM-DTALite

Built upon the integrated AgBM-DTALite modeling framework, a dynamic ramp metering control module was added to the system. The control algorithm employs the time-dependent inputs produced by the dynamic traffic simulation to control the metering rates of those affected ramps. Then simulated traffic dynamics were fed to the agent-based travel behavioral model to update the travel behavior decisions. How the linkage of dynamic traffic assignment models and real-time ramp metering control was developed is documented in Lee et al., (2017) in great detail. The dynamic ramp metering rate of a particular freeway on-ramp was controlled by a series of equations derived using the ALINEA algorithm. Based on the dynamic traffic assignment performed in DTALite, minute-by-minute density, queue length, and volume of each link were simulated. These pieces of information were then employed in ALINEA. The employed ALINEA algorithm estimates the time-dependent ramp metering rate r(t) at time *t*:

$$r(t) = r(t-1) + K_R\left[\hat{O} - O_{out}(t)\right] \tag{2-a}$$

$$\text{s.t.} \quad r_{\min} \le r(t) \le r_{\max} \tag{2-b}$$

In the formulation, KR denotes the regulatory parameter; $\hat{O}$ denotes the critical occupancy; O_{out} denotes the downstream occupancy; r_{min} and r_{max} are the predefined minimum metering rate and maximum metering rate, respectively. ALINEA/Q algorithm extends the ALINEA method to further consider the queue length on the freeway mainline.

$$r'(t) = -\frac{1}{T}\left[\hat{w} - w(t)\right] + d(t-1) \tag{3-a}$$

$$r''(t) = r(t-1) + K_R\left[O' - O_{out}(t)\right] \tag{3-b}$$

$$\text{s.t.} \quad r_{\min} \le r(t) = \max\left\{r'(t), r''(t)\right\} \le r_{\max} \tag{3-c}$$

In this formulation, *T* denotes the time interval; $\hat{w}$ denotes the maximum permissible queue length on ramp; *w* denotes the current queue length on ramp; *d* denotes the demand flow entering a ramp. ALINEA/Q considers further the required entering rate (*r*') from ramps to freeway mainline to prevent excessive queue. An illustrative example is provided in the figure below, where the activation/deactivation thresholds are highlighted. If the ramp queue length becomes too long and spills back to local streets, the meter is deactivated. The downstream density and speed figures depict that this control algorithm is effective in mitigate freeway downstream congestion.

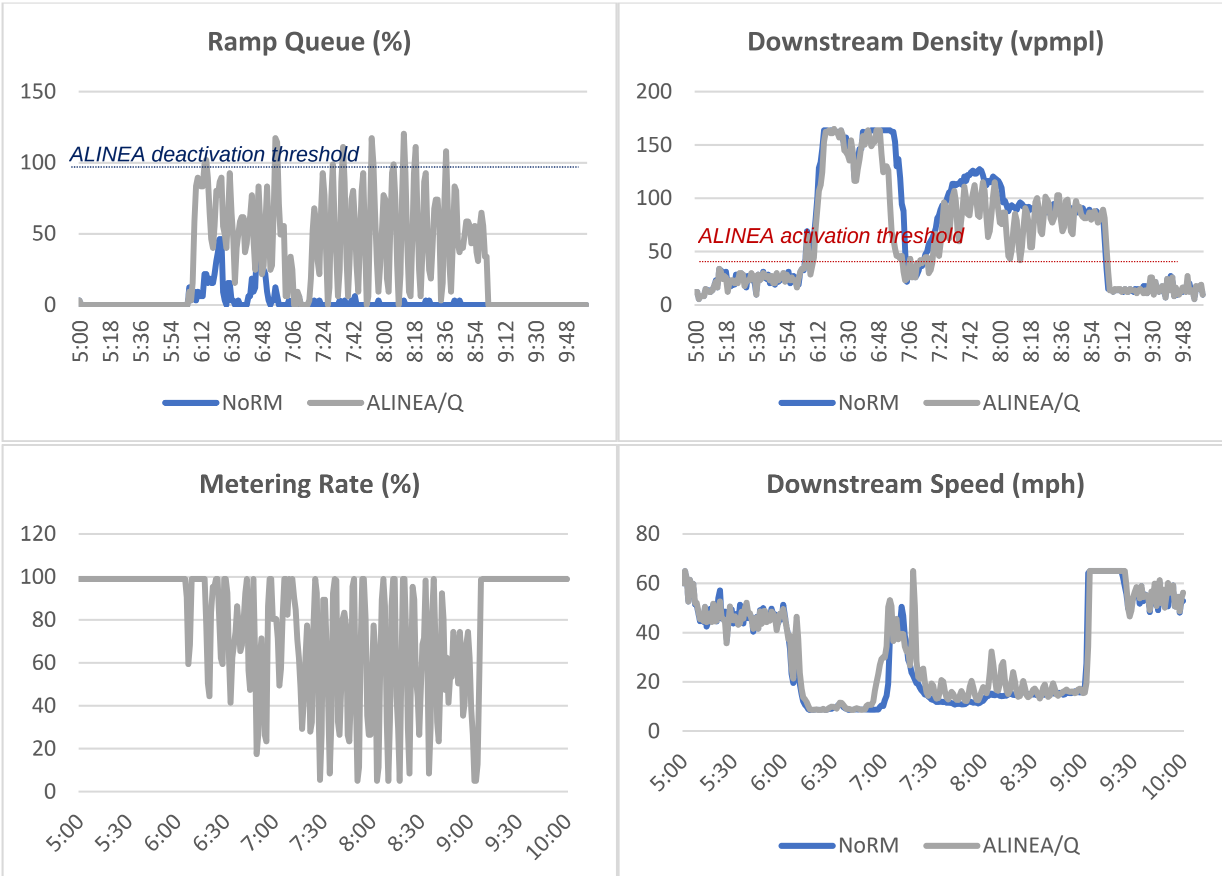


Figure 7. An example of dynamic ramp metering control on the I-270 corridor

The VSL algorithm is illustrated on the right side of the framework shown in Figure 6. The algorithm began with the initialization by identifying the dynamic bottlenecks. The algorithm selected the biggest bottleneck in the network as the location of VSL control. The algorithm used five-minute time interval as the VSL control interval. Two counters were defined for the bottleneck link: T and Q. The counter T is defined using the minute-by-minute link *density*, to identify the moving direction of the bottleneck. It is updated using the following equation:

$$T = T + 1, \text{if } density_t < density_{t-1} \tag{4-a}$$
$$T = T - 1, \text{if } density_t \geq density_{t-1} \tag{4-b}$$

At the beginning of each time interval, T and Q are reset to 0. If the bottleneck keeps growing during the five-minute interval, T decreases and will be negative by the end of the time interval. Similarly, another counter, Q, is defined to identify the moving direction of the queue length, by comparing the link-level queue length at time interval t and t-1.

$$Q = Q + 1, \text{if } Q_t < Q_{t-1} \tag{5-a}$$
$$Q = Q - 1, \text{if } Q_t \geq Q_{t-1} \tag{5-b}$$

The dynamically controlled speed limits for each upstream freeway segment *i* at time *t* are determined based on the following rule-based model. *T* and *Q* are the two counters defined above. Q_t denotes the queue length at the bottleneck at time *t*. Q_k denotes the critical threshold for queue length. V_c^i denotes the lower bound for the controlled speed limit for segment *i*. V_k^i denotes the normal speed limit for segment *i*. The control parameters Q_k and V_c^i are optimized via a simulation-based optimization process for the optimal operations of VSL.

```
if T < 0:
    if Q_t ≥ Q_k:
        if Q < 0:
            V_t^i = max (V_{t-1}^i - 10, V_c^i)
        elseif Q ≥ 0:
            V_t^i = max (V_{t-1}^i - 5, V_c^i)
    elseif Q_t < Q_k:
        V_t^i = V_{t-1}^i
elseif T ≥ 0:
    if Q_t ≥ Q_k:
        V_t^i = V_{t-1}^i
    elseif Q_t < Q_k:
        V_t^i = max (V_{t-1}^i + 5, V_k^i)
```

Figure 8. The pseudo code for variable speed limit control algorithm

A major advantage of the rule-based model is its explicitness and thus can be explained with ease. For instance, the first control rule suggests that if the counter *T* and *Q* are negative and the queue length at the bottleneck is higher than the critical threshold, the speed limit should be reduced by 10 mph until it reaches the lower bound of the speed limit. The density counter *T* is found to be the most dominant control variable, compared to the queue length counter *Q*.

4. SCENARIO ANALYSIS RESULTS

4.1. ATM Scenario Definition

The following figure illustrates the locations where ramp metering was proposed and evaluated. There were 18 ramp metering locations on the SB direction and 14 ramp metering locations on the NB direction.

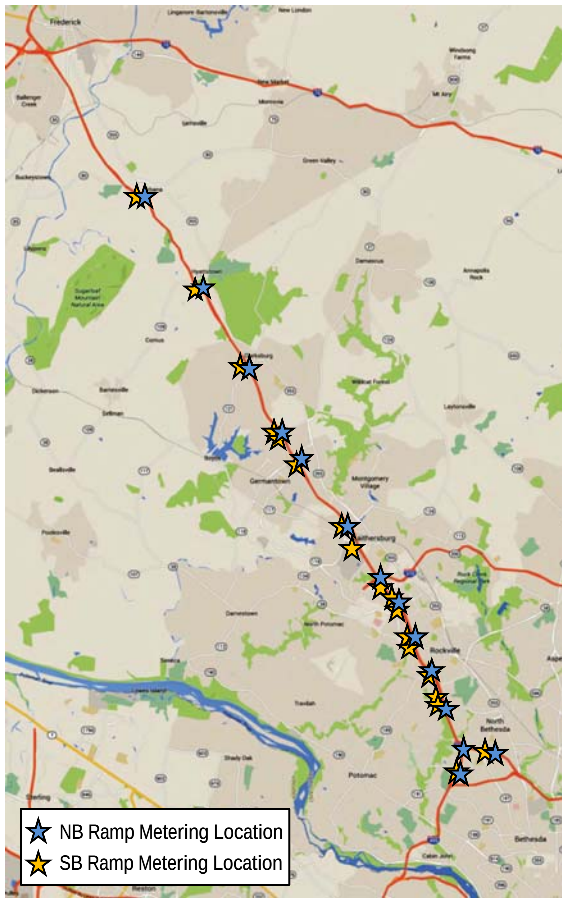


Figure 9. Illustration of the locations of dynamic ramp metering control on I-270

In addition to the ramp metering, other simulated ATM and mobility improvement include Variable Speed Limit (VSL) and various roadway improvements including lane additions, extended acceleration and deceleration lanes, and auxiliary lanes that are proposed in certain locations along the I-270 corridor.

To fully evaluate the reliability and robustness of the ATM strategies, the team used the six day-of-the-week models introduced in Section 3 and designed various travel demand scenarios ranging from 90% of the total OD demand (to represent a low-demand simulation scenario) to 110% of the total OD demand (to represent a high-demand simulation scenario). The simulation of these scenarios constructed a confidence interval with upper/lower bounds for each performance metrics.

4.2. Simulation Results for Ramp Metering and Variable Speed Limits

First a quantification of the impact of I-270 ramp metering and VSL control was completed by comparing the no-build scenario and the VSL only and the ramp metering only scenarios. The following performance measures were used to quantify the impact on I-270 mainline:

- Travel time (min.): average corridor-level travel time in minute, between I-70 junction and I-495 junction.
- Speed (mph): the overall weighted-average travel speed on the corridor.
- Density (vpmpl): the overall weighted-average density (in vehicle per mile per lane).
- Delay changes (%): the reduction of total delay (in minute) compared to the no-build scenario.

To quantify the impact on entrance ramps, travel time and queue length on the ramp were used as the performance measures. These metrics are reported in Table 4 and Table 5, for the extended AM peak and the extended PM peak, respectively. For each metric, the data is reported an average number and a 95% confidence interval that is derived from the multiple random seeds and simulation runs based on different day-of-the-week models and different OD demand levels.

Table 4. Performance Measures (Extended AM Peak Hours, 5:00 AM – 10:00 AM)

	I-270 SB Freeway Mainline				I-270 SB Entrance Ramps	
	Travel Time (min.)	Speed (mph)	Density (vpmpl)	Delay Changes (%)	Travel Time (min.)	Queue Length (veh)
No-Build	47.6 (31.2, 60.2)	55.7 (50.8, 59.9)	35.3 (22.7, 49.5)	-	0.6 (0.4, 1.0)	3.3 (0.4, 9.6)
VSL Only	46.1 (31.0, 58.8)	54.7 (50.4, 59.7)	34.5 (22.8, 48.7)	-7.6 (-11.4, -5.3)	0.57 (0.46, 0.77)	2.3 (0.8, 5.8)
Ramp Metering	42.9 (30.6, 55.4)	56.8 (52.1, 60.1)	32.3 (22.3, 45.9)	-15.6 (-21.4, -13.3)	1.0 (0.5, 1.7)	7.6 (2.3, 15.6)

Table 5. Performance Measures (Extended PM Peak Hours, 2:00 PM – 7:00 PM)

	I-270 NB Freeway Mainline				I-270 NB Entrance Ramps	
	Travel Time (min.)	Speed (mph)	Density (vpmpl)	Delay Changes (%)	Travel Time (min.)	Queue Length (veh)
No-Build	39.0 (32.3, 46.4)	58.4 (56.5, 60.4)	25.9 (20.0, 31.8)	-	0.53 (0.50, 0.60)	4.0 (2.5, 5.7)
VSL Only	38.5 (32.4, 46.3)	57.8 (56.1, 59.9)	25.5 (20.0, 31.7)	-2.0 (-4.3, -1.4)	0.53 (0.50, 0.60)	3.9 (2.3, 5.7)
Ramp Metering	38.4 (32.2, 46.3)	58.6 (56.4, 60.4)	25.4 (19.8, 31.6)	-1.6 (-6.8, -0.1)	0.59 (0.52, 0.61)	4.5 (2.8, 5.6)

The impacts on peak-hour traffic from the proposed VSL and adaptive ramp metering controls were estimated to be significant, especially during the AM peak hours. VSL and ramp metering can reduce the delay by 7.6% and 15.6% during the AM peak. About 5,000 hours and 10,000 hours of total vehicle hours traveled can thus be reduced daily. The reduction percentages for the delays during PM peak hours were 2.0% and 1.6%, respectively, a much less significant saving compared to the finding for the AM peak hours. There were two major reasons that lead to this discrepancy. First, a flatter distribution of the travel demand for PM period was observed for the I-270 corridor. While the ATM is a dynamic strategy that mitigates congestion by moving traffic spatially and/or temporally, the effectiveness was much reduced due to the flat temporal distribution of PM travel demand. Another major reason was on the on-ramps. Unlike the AM peak period when the on-ramps are contributing a large amount of traffic to the I-270 mainline, the traffic volume during the PM peak period mainly came from the upstream freeway segment. Only a small number of vehicles were merging from the on-ramps in the peak direction (I-270 NB). In this regard, ramp metering control, which is very effective during the AM period (-13.3% ~ -21.4% delay reduction), becomes much less influential (-0.1% ~ -6.8% delay reduction).

4.3. Performance Measures of the Overall Impacts

The overall impacts from the ATM scenario where ramp metering, VSL, and the proposed roadway improvements are combined and summarized in Table 6. The ATM scenario reduced the AM average I-270 corridor travel time by 21% (from 47.6 min to 37.6 min), reducing the delay by 32.8%. The PM average corridor travel time is reduced by 14% (from 39.0 min to 33.6 min) while the delay was reduced by 15.2%.

Table 6. Performance Measures of the ATM Scenario

	I-270 Freeway Mainline				I-270 Entrance Ramps	
	Travel Time (min.)	Speed (mph)	Density (vpmpl)	Delay Changes (%)	Travel Time (min.)	Queue Length (veh)
AM No-Build	47.6	55.7	35.3	-	0.53	3.3
AM ATM Scenario	37.6	58.4	27.6	-32.8%	0.60	3.4
PM No-Build	39.0	58.4	25.9	-	0.55	4.0
PM ATM Scenario	33.6	60.0	19.7	-15.2%	0.46	1.4

Figure 10 showcases the corridor travel times of the I-270 (between I-70 and I-495) at the different time of day. In the AM and PM, the travel times for the I-270 SB direction and the NB direction are shown. Above the X axis, the travel times for the no-build scenario and the ATM scenario are compared together, while the differences between the two scenarios are illustrated by the curves below the X axis. The travel time reduction was more significant during the AM period. By examining the different curves, the travel time saving was constantly above the 20% line between 6:30 AM and 9:30 AM, a three-hour time period. Peak period travelers could save up to 25 minutes southbound from I-70 to I-495 at around 7:00 AM. During the PM peak, the travel time saving was above the 20% line between 4:30 PM and 5:45 PM. The travel time saving could be as high as 16 minutes from I-495 to I-70 at around 5:15 PM. These numbers were largely in line with the I-270 innovative transportation management planning proposal. The research determined that the travel time-saving estimate in this project was slightly smaller than the 30-minute time saving estimated in the proposal mainly for two reasons: 1) departure time responses and peak concentration effect were incorporated in this project, creating a rebound effect on the peak-hour congestion levels; 2) ramp metering/VSL algorithms could be further enhanced with advanced coordination and optimization to achieve even higher effectiveness in reducing the peak-hour congestion. This will be further discussed in the subsequent sections.

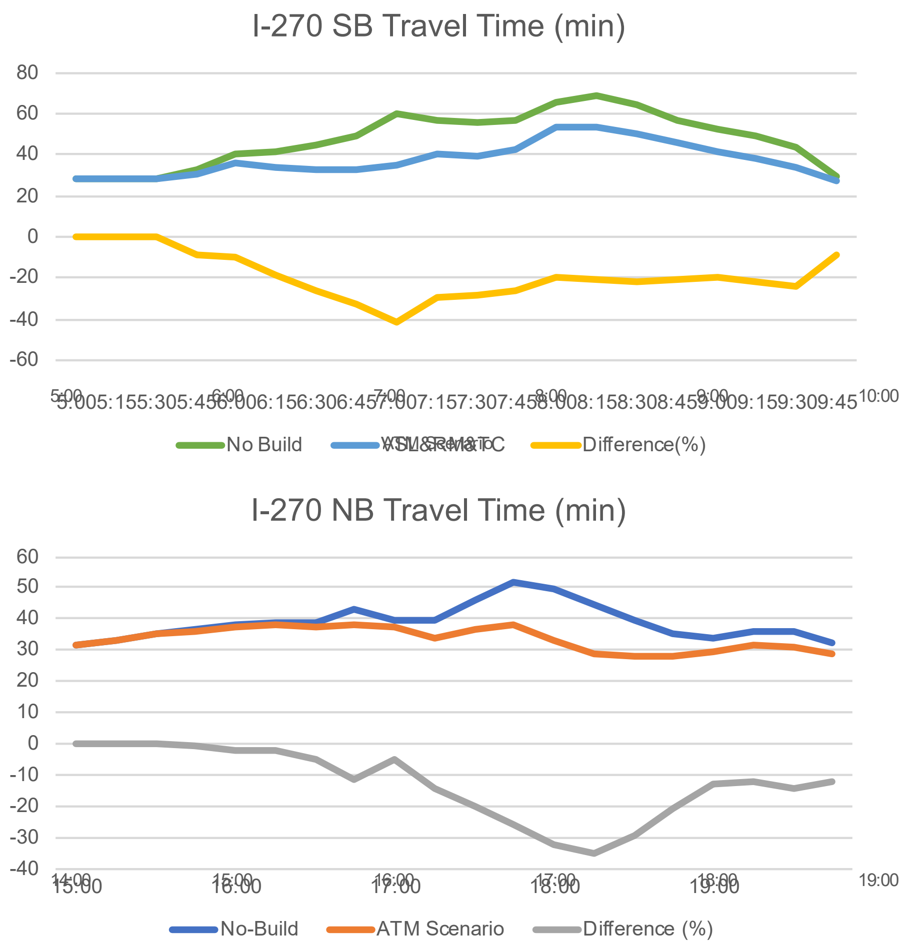
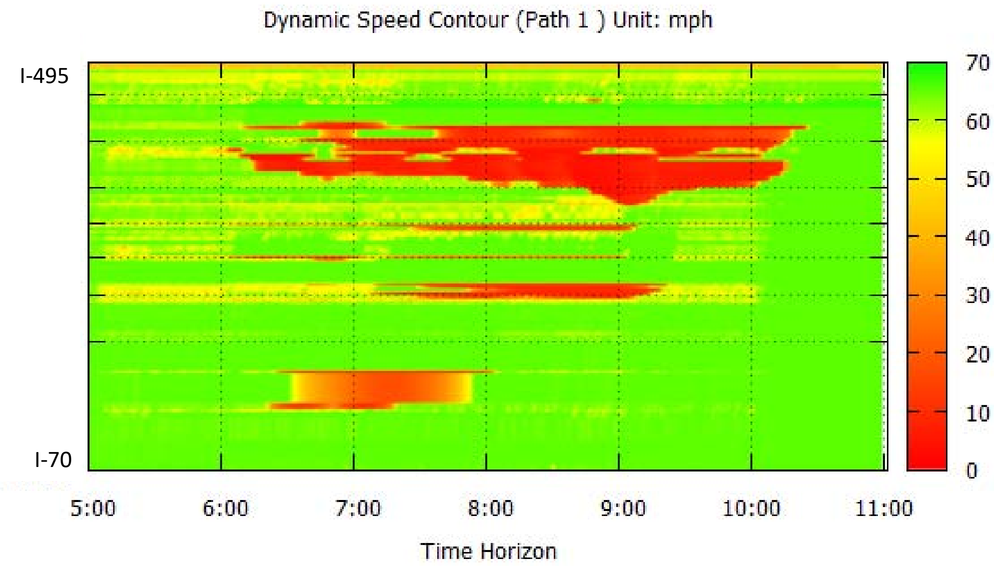
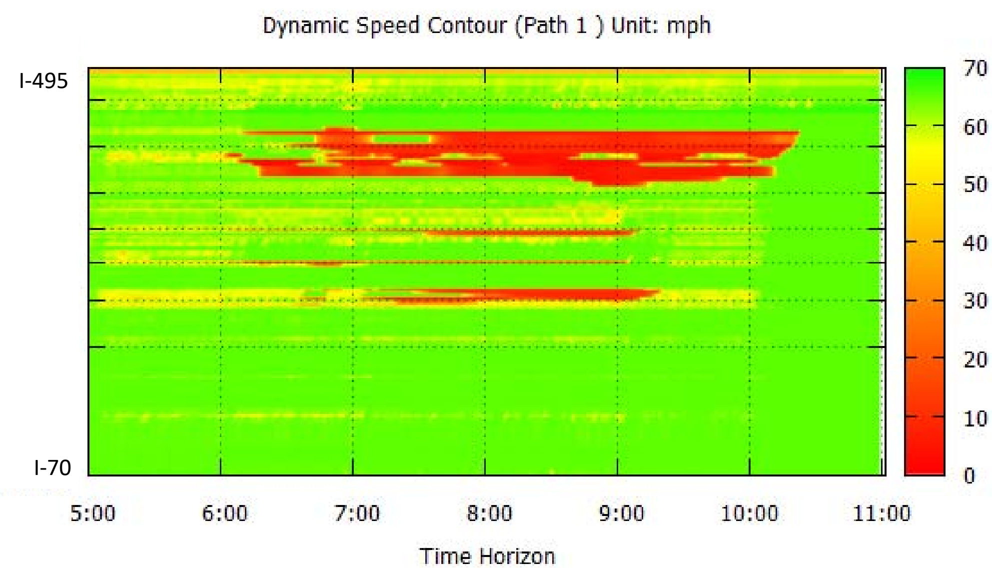


Figure 10. I-270 peak direction travel time (between I-70 and I-495) by time of day (No-Build scenario, ATM scenario, and the difference)

With the integrated AgBM-DTALite model, the research could also evaluate the bottleneck removal potential of implementing the ATM strategies. Figure 11 illustrates the simulated speed contour on a space-time diagram of the no-build scenario and the ATM scenario. The most significant finding was that the bottleneck at the MD-109 (Hyattstown area) has been removed in the ATM scenario (the red-colored contour area near the bottom of Figure 11a). The other congested areas were also found greatly improved, especially the most congested area between I-370 and the I-270 spur. These findings are found in compliance with the I-270 innovative transportation management planning proposal as well, while our simulation shows slightly higher level of congestion.



a. Time-space speed contour of I-270 corridor (no-build scenario)



b. Time-space speed contour of I-270 corridor (ATM scenario)

Figure 11. Time-space diagrams of speed contour for no-build and ATM scenarios

4.4. Travel and Driving Behavior Analysis

4.4.1. Departure Time Adjustments and Peak Spreading

The traffic improvements under the ATM scenario are likely to cause changes in travel behavior. The AgBM-DTALite model was applied and run until the Behavioral User Equilibrium (BUE) was reached. It was found that departure time adjustment was the most significant behavioral shift, compared to modal shift and route changes. It is reasonable that people were more willing to reconsider their departure times, especially when the morning commute was significantly improved due to those ATM implementations. Commuters who originally departed earlier in the morning for fixed work schedules now may leave later, thanks to the up to 25-minute travel time saving along the corridor. For the same reason, travelers who originally chose to depart later to avoid peak traffic now may depart earlier so that they could get to their destinations earlier for different activities. The departure time patterns converged at BUE are illustrated in Figure 12.

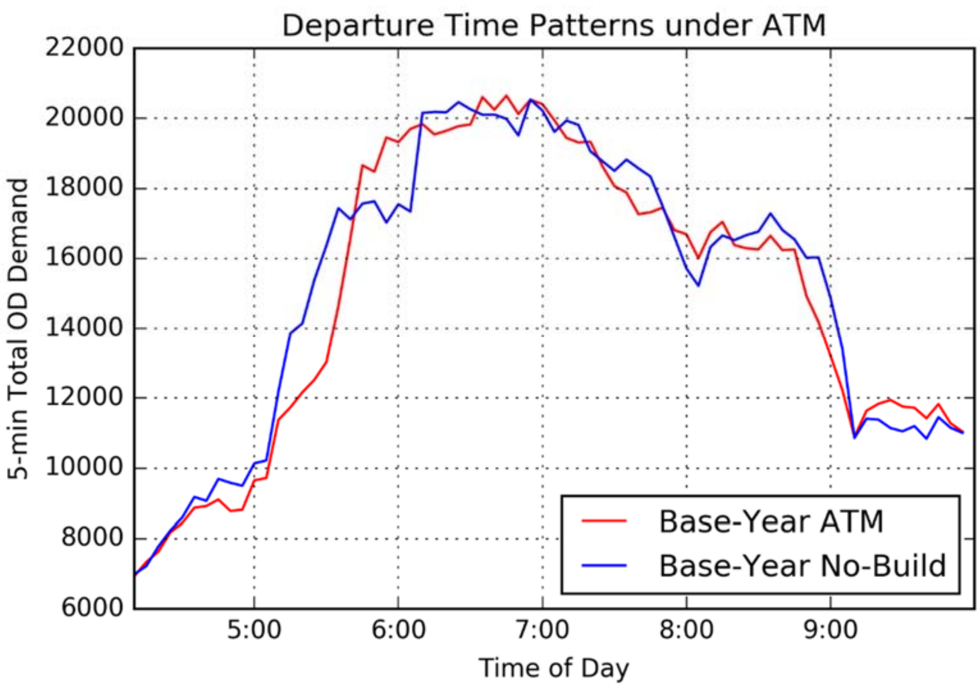


Figure 12. Departure time shifts under the ATM scenario and the peak concentration

It is shown in the figure that the new AM peak-hour period is formed roughly between 5:45 and 8:45. Compared to the original AM peak (roughly between 5:30 and 9:00), the new departure time patterns exhibit a peak concentration phenomenon. About 4% of the travelers have switched from shoulder peak hours to the peak, according to the behavioral analysis. While important for understanding the true impact and behavioral influences of the ATM strategies, this model sensitivity on dynamic departure times is usually missing from the transportation planning and operations analysis, which could lead to bias. If the departure time shifts are assumed away, a more significant travel time saving may be found in the simulation. Instead, the AgBM-DTALite introduces the realistic behavioral foundation that finds the peak concentration and a rebound effect that leads to higher travel demand and less travel time saving during the peak hours. It is worth noting that although the travel time saving is reduced due to the readjusted peak-hour travel demand, the utility levels of the individual travelers could be improved.

4.4.2. Driving Behavior Analytical Tool

The high-resolution GPS trajectory data – one-second sampling interval between GPS waypoints - was collected by vehicle fleet managed by the research team. Each vehicle was equipped with an embedded GPS device. For the year of 2017, the vehicle fleet collected 4,593 trips with 5.2 million GPS waypoints. The team then reconstructed and visualized the trajectories. The spatial coverage of the collected GPS trajectories is shown in Figure 13. The highlighted areas indicate more frequently visited areas by the subject vehicles.

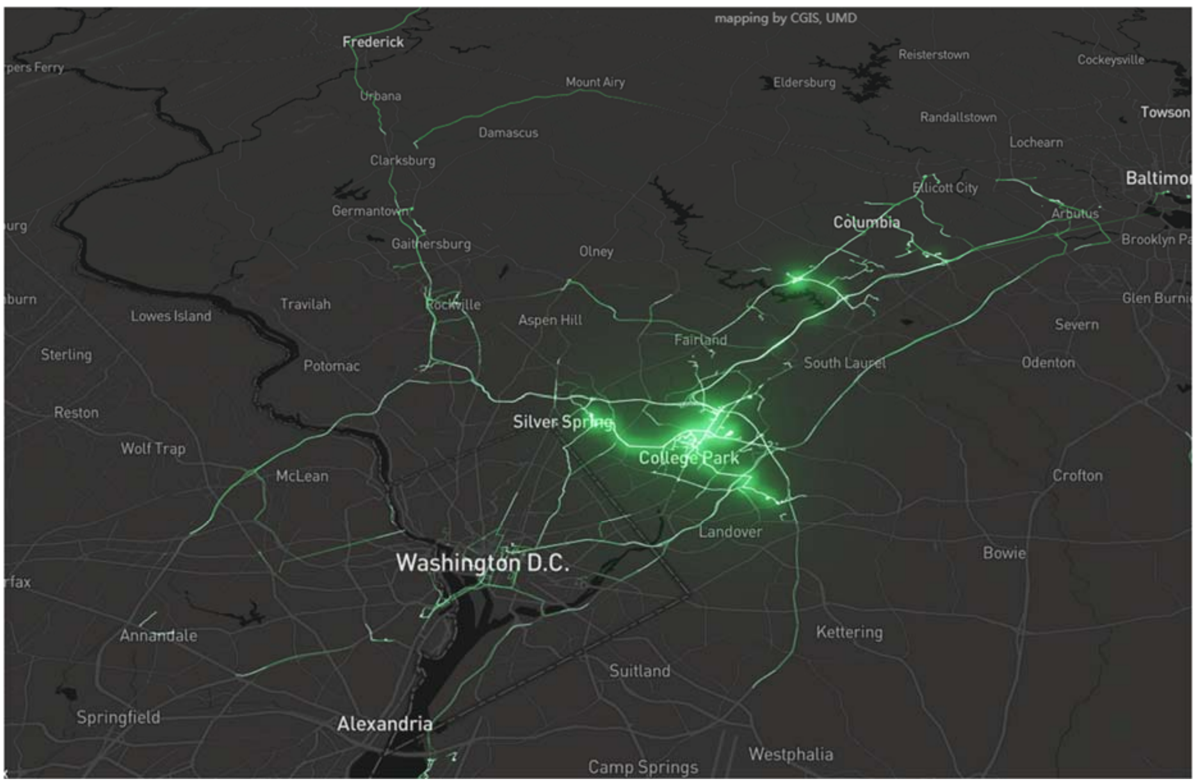


Figure 13. Spatial distribution of the collected GPS trajectory data

Using the collected trajectories, the research team developed a collection of Python modules that convert raw GPS waypoints into driving behavior (e.g., acceleration, deceleration, turning). The trajectory analytic module can perform the following tasks:

- Based on the speed and acceleration of each GPS waypoint, the coordinates and time of GPS waypoints that exceed certain acceleration thresholds (e.g., $0.28/m^2$, which is the 75 percentile of acceleration values of all the 2017 GPS waypoints) were extracted.
- Calculate the driving direction of vehicles at each sampled GPS waypoint.
- Transform a GPS trip that consists of a collection of GPS waypoints, into a sequence of spatiotemporal driving behaviors (e.g., speed changes, jerk, direction change).

Figure 14 below shows the correlation between different driving behaviors, for example, acceleration above 1 m^2 and the average speed of each trip.

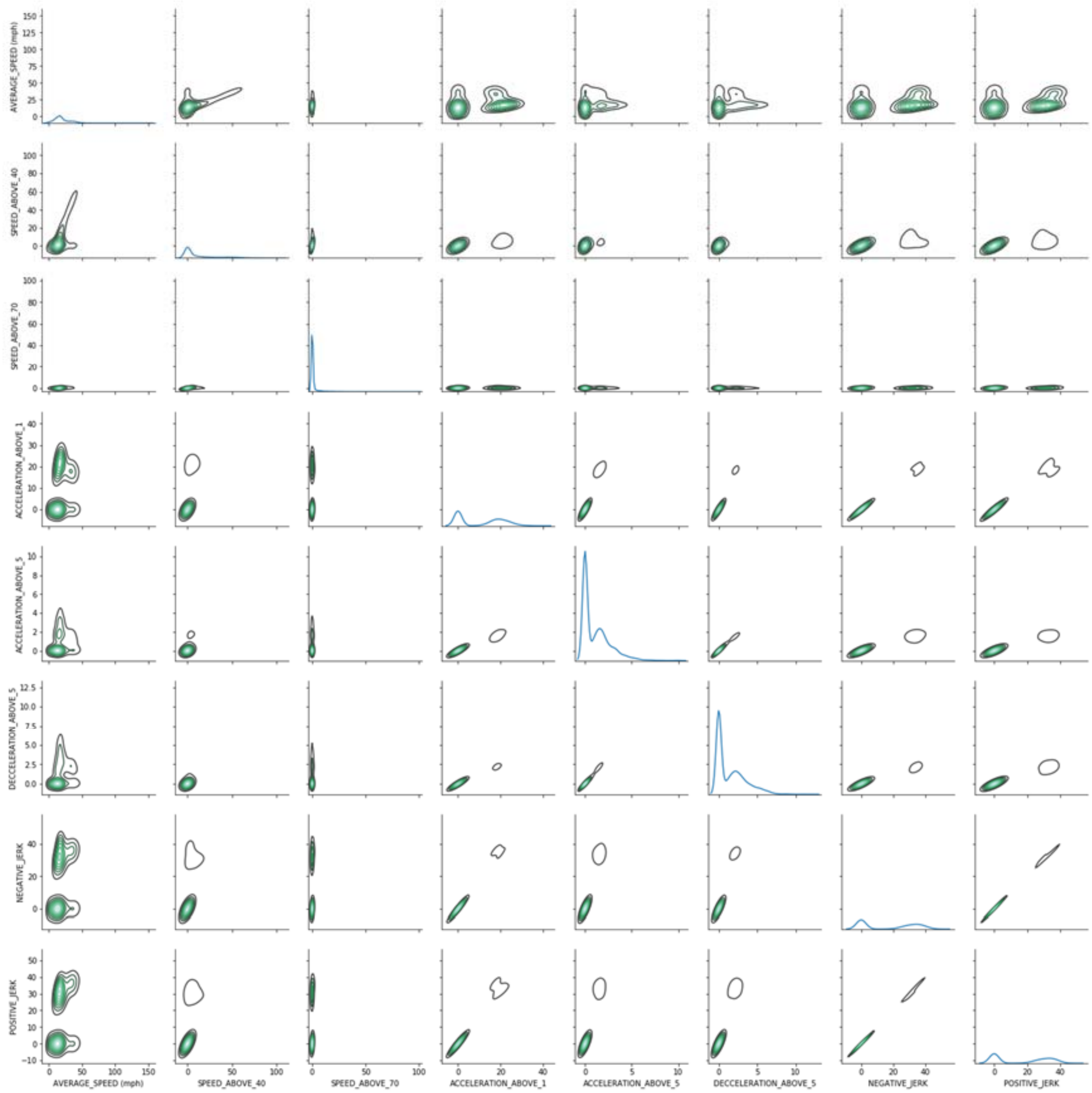


Figure 14. Correlation of different driving behavior

From Figure 14, it was found that sudden acceleration/deceleration behavior (e.g., "ACCELERATION_ABOVE_5", "DECELERATION_ABOVE_5") had strong associations with driving behavior such as positive/negative jerk. In other words, if a driver tends to accelerate or decelerate frequently, he/she will more likely have positive or negative jerk behavior. On the other hand, the average speed of a GPS trip had no strong association with the number of times a driver accelerates or decelerates.

The research team has collected the Maryland statewide vehicle accident data[1] for 2017. After

[1] https://data.maryland.gov/browse?q=crash&sortBy=relevance

preprocessing, built a spatiotemporal database for these vehicle incidents. There are 113,192 vehicle crashes reported during 2017. Figure 15 shows the spatial distribution of these crash incidents.

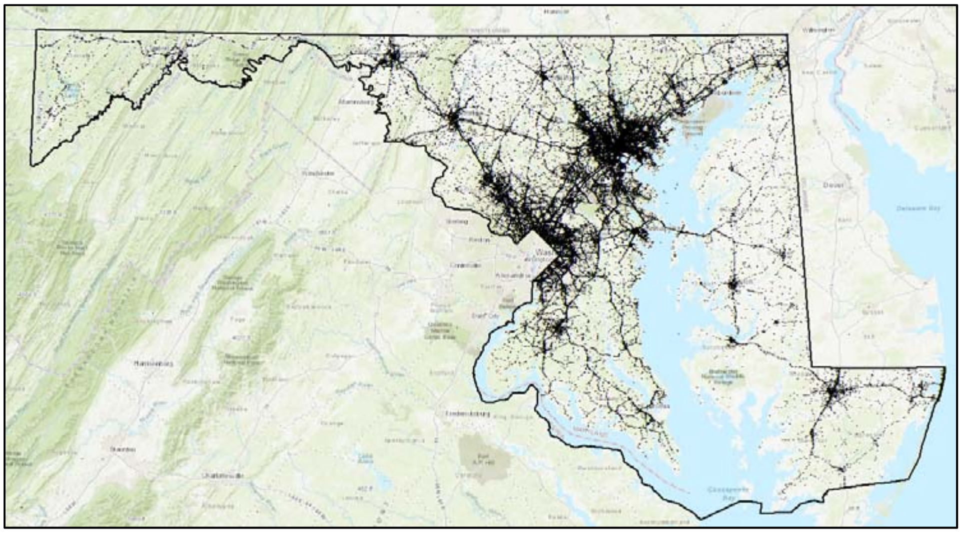
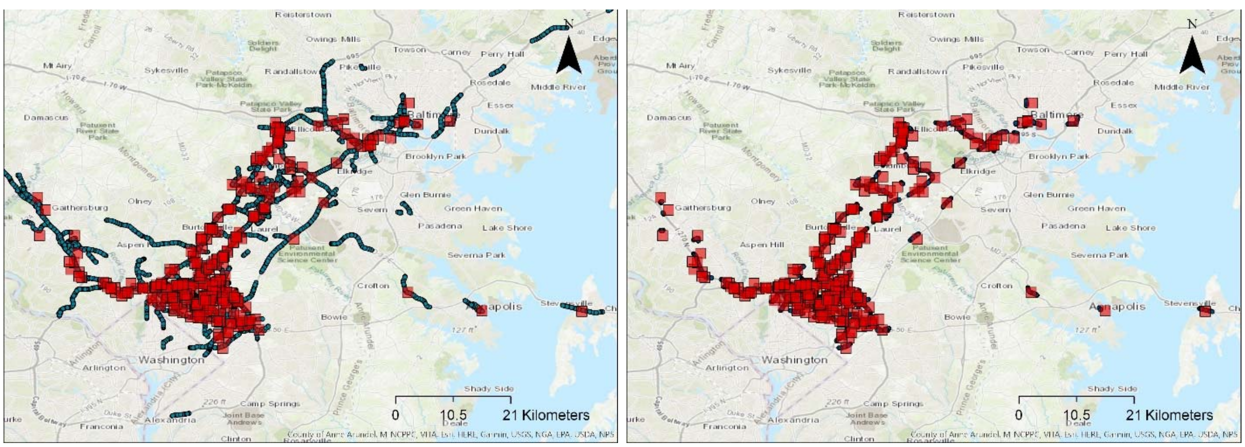


Figure 15. Spatial distribution of vehicle crash events during the year of 2017



a.

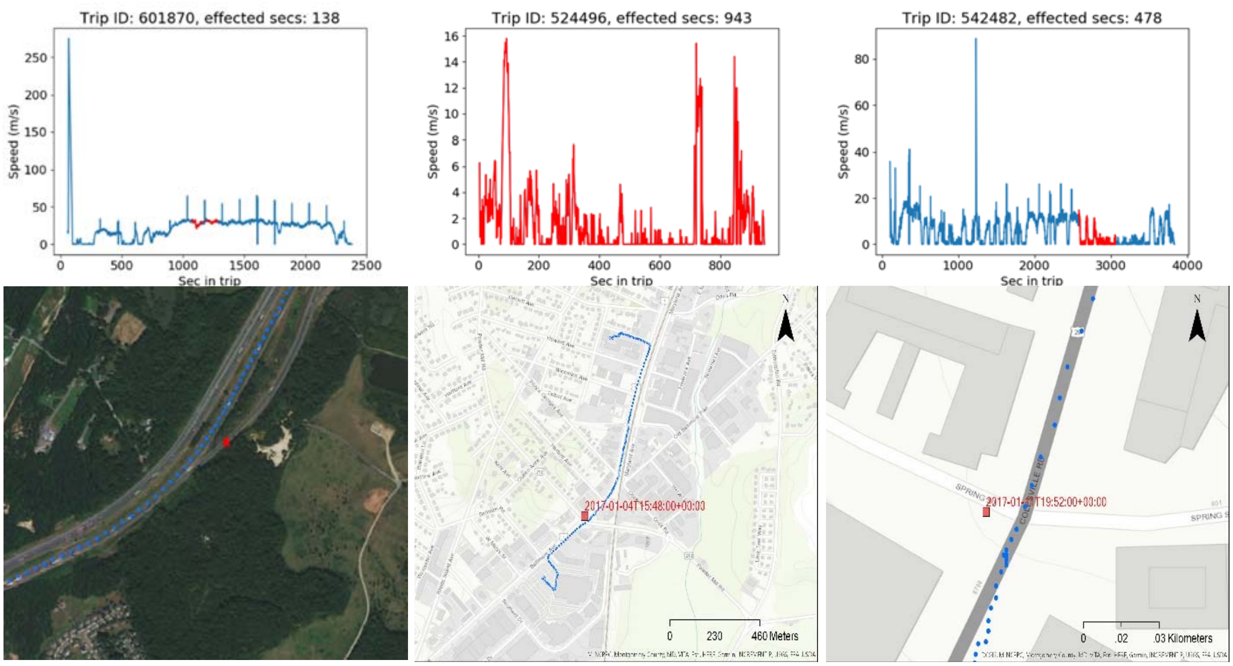
b.

Figure 16. Spatial distribution of potentially impacted GPS waypoints by incidents (a) results filtered by the 3000 m & 60 min. constraints; (b) results filtered by the 1000 m & 30 min. constraints

Based on the location and time of each individual crash incident, spatiotemporal searching was applied to retrieve those GPS waypoints that could be impacted by crash incidents. Two different spatiotemporal constraints were tested to limit the search scope. The retrieved results are:

- spatial and temporal constraint 1: 3000 meters and 60 minutes (depicted in Figure 16a). 1,391 (30.3%) trips and 638,574 waypoints were retrieved under this filter.
- Spatial and temporal constraint 2: 1000 meters and 30 minutes (depicted in Figure 16b). 405 (8.8%) trips and 265,926 waypoints were retrieved under this filter.

Based on applying the second spatiotemporal constraint, we compared and analyzed the characteristics of impacted trips. We identified three different scenarios where drivers could encounter a crash incident that could impact their driving, as depicted in Figure 17.



(a) (b) (c)

Figure 17. Different scenarios where a crash incident can occur in the context of driving: (a) no impact; (b) slow down with direct impact; (c) slow down with indirect impact

Figure 17(a) showed the case where a GPS trajectory is within the spatial and temporal vicinity of a crash incident, but the driving speed is not significantly impacted. The accident is sufficiently off the driving lanes that speed of travel was not impeded. Figure 17(b) illustrated a different case where a GPS trajectory passed through or by a crash incident on the same road and speed is slowed, while a third case was when a crash incident occurred on another road that was close enough to still have an impact on speed (Figure 17c). In both these latter cases, driving slowed down significantly. The results demonstrate that the spatial relationship between crash incidents and the driving trajectory is an important factor in understanding the impact of crash incidents on traffic flow. In this analysis, the team primarily focused on the impact of crash incidents on traffic. The research can also incorporate other types of external event data to produce a more comprehensive understanding of the factors that impact driving behaviors.

5. CONCLUSIONS

The Maryland Transportation Institute (MTI) research team developed an integrated travel behavior and dynamic traffic assignment modeling tool at the mesoscopic level, the AgBM-DTALite, and adapted the tool for real-time and dynamic analysis of active traffic management (ATM) strategies. The model was fully calibrated and validated using disaggregated data collected in the base year of 2015, including hourly traffic counts, corridor-level travel times aggregated in 15-minute intervals, individual vehicle trajectories, and energy consumption at the trip-level. Then the model was applied to evaluate several proposed ATM strategies on the I-270 corridor, including Variable Speed Limit (VSL), dynamic ramp metering controls, as well as various roadway improvements (lane addition, the extension of acceleration/deceleration lanes etc.). A series of performance measures were developed and employed to assess the effectiveness of each ATM strategy and evaluate the combined effect. Travel behavioral responses were also modeled and measured, including the departure time responses and the driving behavior.

The major innovations in this ATM research were three-fold:

- The travel behavioral models were tightly integrated into the simulation of ATM, allowing the model to assess different aspects of behavioral responses to the ATM strategies.
- The AgBM-DTALite integration and its embedded Behavioral User Equilibrium (BUE) greatly improved the computational efficiency of the mesoscopic simulation, which granted the capability of large-scale applications, as well as the high resolution at the minute-by-minute level.
- The minute-by-minute tight integration of ATM algorithms in the AgBM-DTALite was an innovation. With this, mesoscopic models could be adopted to evaluate real-time transportation systems management and operations (TSM&O).

With these research innovations, the team applied the AgBM-DTALite to evaluate I-270 innovative transportation management ATM strategies. By applying the modeling tool, significant departure time behavioral changes were found in response to ATM and the subsequent changes in traffic conditions. At the aggregate level, a “peak concentration” phenomenon was identified in the AM peak. Due to the mitigated peak congestion, current travelers were more willing to switch back to peak-hour departure times to avoid too early or late schedule. The side effect was the slightly increased peak travel times, compared to the conditions where travelers’ departure time patterns were fixed. Modal shifts and route changes were found much less significant. This behavioral sensitivity could certainly play an important role in current and future ATM and TSM&O analyses, as travel behavioral patterns are being reshaped and will influence the traffic conditions and decision-making in return. The team also developed a Python-based analytical toolbox to evaluate driving behavior and its spatial-temporal (space-time) interrelationship with traffic and incidents. With these analysis tools, it was found that the I-270 ATM scenario (including VSL, ramp metering, and roadway improvements) could reduce the AM average I-270 corridor (i.e. from I-70 to I-495) travel time by 21%, reducing the delay by 32.8%. The PM average corridor travel time was reduced by 14% while the delay was reduced by 15.2%.

As potential next steps, the following promising research directions were identified by the research team. The AgBM-DTALite could be further developed as a real-time and data-driven modeling suite for TSM&O applications and decision-support for Maryland. The integrated model with ATM control mechanisms was application ready via this project, while the real-time data and calibration capabilities were developed via several parallel efforts. Another promising application lies in the advanced travel demand management. The incenTrip tool with real-time traveler information and incentives could be deployed on I-270 to further enrich the ATM. The incenTrip could dynamically incentivize multimodal and shared-/smart-mobility travel to address congestion or other needs. Lastly, advanced data collection for ATM is also crucial. Fiber optic sensing for the ATM deployment could lead to no delay in real-time speed measurements and continuous speed measures along the entire corridor, which could be a promising direction.

REFERENCES

Ahn, S., R. L. Bertini, B. Auffray, J. H. Ross and O. Eshel, Evaluating the Benefits of a System-Wide Adaptive Ramp-Metering Strategy in Portland, Journal of Transportation Research Board, Transportation Research Record, Vol., No. 1, pp. 47-56, 2012.

Allaby, P., B. Hellinga and M. Bullock, Variable Speed Limits: Safety and Operational Impacts of a Candidate Control Strategy for an Urban Freeway, IEEE Transactions on Intelligent Transportation Systems, vol. 8, no. 4, pp. 671-680. 2007.

Asare, S., and B. Smith. Identifying and Prototyping Integrated Corridor Management (ICM) Strategies for Application in Virginia, Virginia Department of Transportation Research Report, 2014. VCTIR 14-R10.

Chu, L., H.X. Liu, W. Recker, and H. M. Zhang, Performance Evaluation of Adaptive Ramp Metering Algorithms Using Microscopic Traffic Simulation Model, California Department of Transportation, Technical Report, 2005.

Francis, C., 2013. ITS Multimodal Initiatives in Virginia, HRTO Subcommittee Meeting, Hampton, VA, June 11, 2013, Virginia Department of Transportation.

Fudala, N.J. and M.D. Fontaine, Work Zone Variable Speed Limit Systems: Effectiveness and System Design Issues. Virginia Transportation Research Council Report, 2010.

Georgia Department of Transportation website. Safety & Operation. Retrieved from http://www.dot.ga.gov/DriveSmart/SafetyOperation/Documents/RampMeters/Location-Schedules.pdf

Hallenbeck, T.P. and K. Benouar. 2015 Ramp Metering Development Plan Report, California Department of Transportation, 2016.

Kansas and Missouri Department of Transportation. Ramp Metering 2011 Evaluation Report, 2011

Lee, C., B. Hellinga, and F. Saccomanno, Assessing Safety Benefits of Variable Speed Limits, Journal of the Transportation Research Record, No. 1987, pp. 183-190, 2004.

Lee, M., Zhu, Z., Xiong, C. and Zhang, L. Integrating dynamic traffic assignment with ramp metering control for large-scale corridor management. Presentation at the 2017 TRB Annual Meeting, 17-05671. Washington D.C., Jan 8-12, 2017.

Lyles, R.W., W.C. Taylor, D. Lavansiri, and J. Grosskalaus, A Field Test and Evaluation of Variable Speed Limits in Work Zones, Transportation Research Board Annual Meeting. 2004.

Minnesota Department of Transportation (MNDOT), Twin Cities Ramp Meter Evaluation Final Report, 2001.

Nezamuddin, N., Jiang, N., Zhang, T., Waller, S.T., Sun, D. 2011. Traffic Operations and Safety Benefits of Active Traffic Strategies on TxDOT Freeways. Project Report, Texas DOT

North Carolina Department of Transportation website. On-ramp Signals. Retrieved from https://www.ncdot.gov/projects/onrampsignals/

PB Americas, Inc., Carter+Burgess, EarthTech, Inc., and Telvent Farradyne, 2007. Active Traffic Management (ATM) Feasibility Study, Washington State Department of Transportation.

PB and University of Maryland . Managing a Corridor. Presentation at SHRP2 Project L36 Regional Operations Forums pilots. June 2014

Riffkin, M., T. McMurtry, S. Heath, and M. Saito, Variable Speed Limit Signs Effects on Speed and Speed Variation in Work Zones. Utah Department of Transportation Research and Innovation Division Report. 2008.

Robinson, M., Examples of Variable Speed Limit Applications, Speed Management Workshop Notes, 79th Annual Meeting of Transportation Research Board, Washington D.C., 2000.
Sripathi, H., I-95/I-395 Integrated Corridor Management Initiative, Virginia Department of Transportation Workshop Material.
Texas Transportation Institute (TTI). Implementation of Arlington Ramp Metering System, Project Summary Report. 2001.
The Kansas and Missouri Department of Transportation. Ramp Metering 2011 Evaluation Report, 2011
Kansas City Scout. Retrieved from http://www.kcscout.net/RMFAQ.aspx
Virginia Department of Transportation, I-66 Active Traffic Management Project website. Retrieved from http://www.virginiadot.org/projects/northernvirginia/i-66_atms.asp
Waller, S., M. Ng, E. Ferguson, N. Nezamuddin, and D. Sun, Speed harmonization and peak-period shoulder use to manage urban freeway congestion. Federal Highway Administration Report. 2009.
Wisconsin Department of Transportation. Ramp Meters website. Retrieved from http://www.dot.state.mn.us/rampmeter/nationwide.html
Xiong C. and L. Zhang (2013). A descriptive Bayesian approach to modeling and calibrating drivers' en-route diversion behavior. IEEE Transactions on Intelligent Transportation Systems. 14(4). pp. 1817-1824, 2013
Xiong, C., Chen, X., He, X., Lin, X., & Zhang, L. Agent-based en-route diversion: Dynamic behavioral responses and network performance represented by macroscopic fundamental diagrams. Transportation Research Part C: Emerging Technologies, 64, pp. 148-163, 2016.
Xiong, C., Zhou, X., Zhang, L., Mahapatra, S. and Baber, C. AgBM-DTALite: An integrated modeling system of agent-based travel behavior and transportation network dynamics. In Proceedings of the 14th World Conference on Transport Research (WCTR), Shanghai, Jul 10-15, 2016.
Yang, X., Lin, Y., Lu, Y., Zou, N. Optimal variable speed limit control for real-time freeway congestions. Procedia-Social Behavioral Sciences, 2013. 93, 2362-2372.
Zegeye, S.K., B. De Schutter, H. Hellendoorn, and E. Breunesse, Reduction of Travel Times and Traffic Emissions Using Model Predictive Control, Proceedings of the 2009 American Control Conference, St. Louis, Missouri, pp. 5392-5397. 2010.
Zhou, X., & Taylor, J. DTALite: A queue-based mesoscopic traffic simulator for fast model evaluation and calibration. Cogent Engineering, 1(1), 961345, 2014.
Zhu X., C. Robbins, J. Snyder, and J. Podriguez. Operation of Ramp Signaling System – FDOT's Experiences, Florida Department of Transportation, Research Report, 2011.
Zhang, L., et al. 2014. Integrating an agent-based travel behavior model with large-scale microscopic traffic simulation for corridor-level and subarea transportation operations and planning applications. Journal of Urban Planning and Development, 139(2), 94-103.