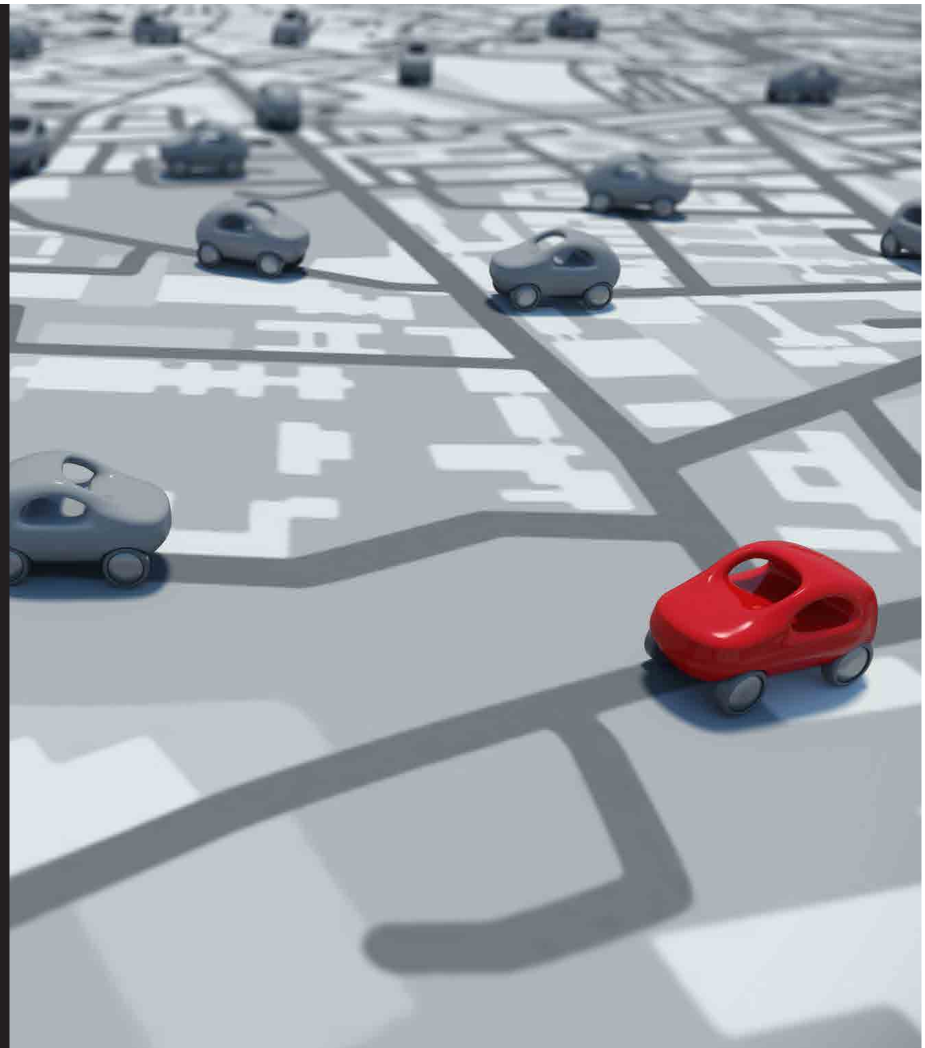

FHWA Research and Technology Evaluation

# Agent-Based Modeling and Simulation

Final Report
November 2018

Publication No. FHWA-HRT-18-042

U.S. Department of Transportation
Federal Highway Administration

## Foreword

The Federal Highway Administration's (FHWA's) Research and Technology Program furthers the FHWA Office of Research, Development, and Technology's (RD&T's) goal of ensuring transparency, accessibility, and responsiveness of RD&T for all stakeholders.

This report examines how FHWA's investment in agent-based modeling and simulation (ABMS) through the FHWA Exploratory Advanced Research Program has increased awareness of and contributed to the development and deployment of the technology.

This report should be of interest to engineers, practitioners, researchers, and decisionmakers involved with the research, design, performance, and management of ABMS.

Hari Kalla, P.E.
Associate Administrator, Office of Research,
Development, and Technology

## Notice



## Quality Assurance Statement



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# TECHNICAL REPORT DOCUMENTATION PAGE

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16. Abstract
The overall purpose of this evaluation was to understand the effect of the Federal Highway Administration's (FHWA's) Research and Technology Program activities on the implementation of agent-based approaches to transportation-related projects and activities. Agent-based modeling and simulation (ABMS) uses individual "agents," typically drivers and agencies, to model changes in transportation networks and systems. Researchers and industry stakeholders view ABMS and the data-collection and validation processes that ABMS requires as a valuable, emerging practice that can be used to advance existing transportation-modeling and simulation techniques. ABMS can also be used for various transportation applications, including planning, operations, and safety countermeasures. As a result, the discipline and community are growing, and usage of ABMS approaches is expanding. The evaluation team assessed the role the FHWA Exploratory Advanced Research (EAR) Program played in this growth and how the EAR Program–funded research led to further developments and advancements. Beginning in 2009, the FHWA EAR Program began investigating the use of agent-based modeling techniques for characterizing driver and traveler behavior. The EAR Program sought to address technological advancements being applied to vehicles within the transportation network.

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# SI* (MODERN METRIC) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | 25.4 | millimeters | mm |
| ft | feet | 0.305 | meters | m |
| yd | yards | 0.914 | meters | m |
| mi | miles | 1.61 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 645.2 | square millimeters | $mm^2$ |
| $ft^2$ | square feet | 0.093 | square meters | $m^2$ |
| $yd^2$ | square yard | 0.836 | square meters | $m^2$ |
| ac | acres | 0.405 | hectares | ha |
| $mi^2$ | square miles | 2.59 | square kilometers | $km^2$ |
| | | **VOLUME** | | |
| fl oz | fluid ounces | 29.57 | milliliters | mL |
| gal | gallons | 3.785 | liters | L |
| $ft^3$ | cubic feet | 0.028 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.765 | cubic meters | $m^3$ |
| | | NOTE: volumes greater than 1000 L shall be shown in $m^3$ | | |
| | | **MASS** | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2000 lb) | 0.907 | megagrams (or "metric ton") | Mg (or "t") |
| | | **TEMPERATURE (exact degrees)** | | |
| $^oF$ | Fahrenheit | 5 (F-32)/9 or (F-32)/1.8 | Celsius | $^oC$ |
| | | **ILLUMINATION** | | |
| fc | foot-candles | 10.76 | lux | lx |
| fl | foot-Lamberts | 3.426 | candela/$m^2$ | cd/$m^2$ |
| | | **FORCE and PRESSURE or STRESS** | | |
| lbf | poundforce | 4.45 | newtons | N |
| lbf/$in^2$ | poundforce per square inch | 6.89 | kilopascals | kPa |

## APPROXIMATE CONVERSIONS FROM SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.039 | inches | in |
| m | meters | 3.28 | feet | ft |
| m | meters | 1.09 | yards | yd |
| km | kilometers | 0.621 | miles | mi |
| | | **AREA** | | |
| $mm^2$ | square millimeters | 0.0016 | square inches | $in^2$ |
| $m^2$ | square meters | 10.764 | square feet | $ft^2$ |
| $m^2$ | square meters | 1.195 | square yards | $yd^2$ |
| ha | hectares | 2.47 | acres | ac |
| $km^2$ | square kilometers | 0.386 | square miles | $mi^2$ |
| | | **VOLUME** | | |
| mL | milliliters | 0.034 | fluid ounces | fl oz |
| L | liters | 0.264 | gallons | gal |
| $m^3$ | cubic meters | 35.314 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.307 | cubic yards | $yd^3$ |
| | | **MASS** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.202 | pounds | lb |
| Mg (or "t") | megagrams (or "metric ton") | 1.103 | short tons (2000 lb) | T |
| | | **TEMPERATURE (exact degrees)** | | |
| $^oC$ | Celsius | 1.8C+32 | Fahrenheit | $^oF$ |
| | | **ILLUMINATION** | | |
| lx | lux | 0.0929 | foot-candles | fc |
| cd/$m^2$ | candela/$m^2$ | 0.2919 | foot-Lamberts | fl |
| | | **FORCE and PRESSURE or STRESS** | | |
| N | newtons | 0.225 | poundforce | lbf |
| kPa | kilopascals | 0.145 | poundforce per square inch | lbf/$in^2$ |

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

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# List of Abbreviations and Acronyms

| Abbreviation/Acronym | Definition |
|---|---|
| ABM | activity-based model |
| ABMS | agent-based modeling and simulation |
| ARC | Atlanta Regional Commission |
| BMC | Baltimore Metropolitan Council |
| BUE | behavior user equilibrium |
| DOE | Department of Energy |
| DTA | dynamic traffic assignment |
| EAR | Exploratory Advanced Research |
| FHWA | Federal Highway Administration |
| FS | fact sheet |
| HTML | Hypertext Markup Language |
| IP | Internet provider |
| ITM | Innovations in Travel Modeling |
| MAG | Maricopa Association of Governments |
| MPO | metropolitan planning organization |
| NASA | National Aeronautics and Space Administration |
| NTL | National Transportation Library |
| PDF | Portable Document Format |
| PI | principal investigator |
| R&T | research and technology |
| SHA | State Highway Administration |
| SHRP2 | second Strategic Highway Research Program |
| TRANSIMS | Transportations Analysis and Simulation System |
| TRB | Transportation Research Board |
| TRID | Transport Research International Documentation |
| TRL | Technology Readiness Level |
| TRR | *Transportation Research Record* |
| UMD | University of Maryland |
| USDOT | United States Department of Transportation |
| VASTO | Evolutionary Agent System for Transportation Outlook |

# Executive Summary

## Purpose of the Evaluation

The overall purpose of this evaluation is to understand the effect of the Federal Highway Administration's (FHWA's) Research and Technology Program activities on the implementation of agent-based approaches to transportation-related projects and activities. Agent-based modeling and simulation (ABMS) uses individual "agents," typically drivers and agencies, to model changes in transportation networks and systems. Researchers and industry stakeholders view ABMS, including the data-collection, assessment, and validation processes that ABMS requires, as a valuable, emerging practice that can be used to advance existing transportation-modeling and simulation techniques. ABMS can also be used for various transportation applications, including planning, operations, and safety countermeasures. As a result, the discipline and community are growing, and usage of ABMS approaches is expanding. The evaluation team assessed the role the FHWA Exploratory Advanced Research (EAR) Program played in this growth and how EAR Program–funded research led to further developments and advancements.

## Program Description

In 2009, the FHWA EAR Program began investigating the use of agent-based modeling techniques for characterizing driver and traveler behaviors. The EAR Program sought to address technological advancements being applied to vehicles within the transportation network. Part of the goal was for ABMS to precisely model the behavior of drivers and address the increase in connected-vehicle and autonomous systems, for which ABMS was especially suited.(2) This effort included hosting a workshop for relevant stakeholders and subject-matter experts. On the basis of a competitive bidding process and the recommendations by FHWA staff, the agency sponsored three research projects investigating this topic: Driver Behavior in Traffic; Evolutionary Agent System for Transportation Outlook; and Agent-Based Approach for Integrated Driver and Traveler Behavior Modeling.(2–4) Upon completion of each project, the EAR Program conducted Technology Readiness Level (TRL) assessment panels to evaluate the outcomes of the research.

## Methodology

In evaluating ABMS, the evaluation team used three primary data sources. First, the team conducted a literature review of publicly available information, including a review of FHWA materials, outreach, and reports. These documents are sourced and discussed throughout this report. The review focused on EAR Program–funded ABMS activities and projects. Second, the evaluation team attended presentations at the 95th Transportation Research Board (TRB) Annual Meeting and the 6th TRB Conference on Innovations in Travel Modeling. Finally, the evaluation team interviewed EAR Program–funded project leaders, FHWA subject-matter experts, TRL assessment panelists, and other stakeholders, such as private modeling consultants.

The evaluation team sought to determine the outcomes and impacts of ABMS, most notably in terms of awareness, adoption, and potential impacts on transportation networks with a particular emphasis on the role EAR Program funding played in generating outputs that led to tangible outcomes and expected impacts. So, how did the EAR Program contribute to the state of the practice of the emerging technology, and what is the potential impact of ABMS moving forward?

# Findings

The evaluation team found that the EAR Program played a significant role in developing interest and awareness of ABMS within the field of transportation. Prior to the EAR Program activities, agent-based modeling was referenced only minimally in transportation contexts and was merely theoretical. On the basis of the research conducted, the EAR Program and FHWA showed the viability of ABMS within the field of transportation. As one interviewee pointed out, the EAR Program and FHWA effectively brought agent-based modeling from other disciplines to transportation.[1]

Significantly, EAR Program–funded researchers are currently working with metropolitan planning organizations and other agencies to further develop and deploy ABMS tools and methods. Since the time the EAR Program began funding ABMS-related work, additional FHWA and Department of Energy (DOE) researchers, academic researchers, and private practitioners have begun to develop and incorporate ABMS models and techniques.

However, barriers to usage, such as funding resources and the development of technical expertise and technological capabilities, exist within the transportation-modeling industry. These barriers have hindered the wide-scale development and deployment of ABMS. Despite this, and largely due to the efforts of the EAR Program, ABMS is viewed as the logical next step in transportation modeling. ABMS has the potential to improve the efficiency and accuracy of transportation models and to advance new technologies, such as automated vehicles and real time–response capabilities.

# Recommendations

Based on these findings, the evaluation team identified the following four recommendations that could facilitate the further adoption of ABMS as well as other FHWA and EAR Program projects or initiatives. The recommendations are as follows:

1. When exploring innovative methods or technology, be careful and deliberate regarding nomenclature and definitions.
2. Establish clear guidelines for project publications, ownership, and accessibility.
3. Establish a framework for outreach and supporting postresearch efforts.
4. Establish a framework for considering postresearch development and applications.

[1]Transportation researcher, phone interview conducted by Greg Bucci, Michael Green, and Chris Calley (evaluation team), January 2017.

# Conclusion

Overall, the EAR Program was the catalyst for the use of ABMS within the field of transportation modeling. Prior to the involvement of FHWA and the EAR Program, ABMS was largely unknown among transportation modelers and researchers. Due in large part to EAR Program–funded research efforts, EAR Program–funded researchers have continued to explore ABMS. Other academic and public researchers, including DOE, have begun applying ABMS to transportation models as well. The impacts, including possible safety and mobility improvements, are yet to be fully determined and will become clearer as the usage and development of ABMS continues. As a result, the full impacts of EAR Program–funded work will likely expand as usage of ABMS grows within the field of transportation.

# 1. Introduction

## 1.1 Evaluation Purpose

The Federal Highway Administration (FHWA) has initiated an effort to evaluate the Research and Technology (R&T) Development Program. Leaders of governmental transportation R&T programs need to effectively communicate the impacts of their programs. The R&T evaluation program helps FHWA assess how efficiently it is meeting its goals and objectives and provides useful data to inform future project selections.

In its initial year, the R&T evaluation program worked with nine FHWA offices to identify projects for evaluation. The FHWA Exploratory Advanced Research (EAR) Program identified research on agent-based modeling and simulation (ABMS) as an area to evaluate. ABMS is an advanced form of computer simulation with the potential to enhance and improve the discipline of transportation modeling. This evaluation assesses three ABMS research projects funded by the EAR Program and additional EAR Program–funded activities related to ABMS.

The overall purpose of this evaluation is to understand the effect of FHWA R&T activities on the implementation of agent-based approaches to transportation projects and activities. The three EAR Program–funded projects—Driver Behavior in Traffic, Evolutionary Agent System for Transportation Outlook (VASTO), and Agent-Based Approach for Integrated Driver and Traveler Behavior Modeling—are distinct but related projects.(2–4) While the projects address modeling of different activities, all three seek to advance the state of the pratice of agent-based approaches within the field of transportation. In addition to the three primary research projects, the EAR Program conducted other activities such as workshops and assessment panels. These activities were considered, and the overall ABMS EAR Program–funded effort was evaluated.

ABMS, including the data-collection, assessment, and validation processes that ABMS requires, is viewed by researchers and industry stakeholders as a valuable, emerging practice that can be used to advance transportation-modeling and simulation techniques and can also be used for various transportation applications, including planning, operations, and safety countermeasures. Specifically, ABMS allows transportation modelers to closely approximate real-world conditions by using *agents* that can learn from *experience* (or previous model simulations) and change their behavior during each iteration of the simulation. As a result, usage of ABMS approaches is expanding within the field of transportation modeling. The evaluation team assessed the role that EAR Program–funded ABMS work played in this growth and how its work has led to further developments and advancements.

Within the *R&T Agenda,* the following three objectives were designed specifically for the EAR Program to address:(5)

- Objective 1: Collaborate with stakeholders from multiple disciplines (both inside and outside the field of transportation) to promote and foster creative, innovative thinking.`
- Objective 2: Promote, fund, and enable higher-risk research with high potential for revolutionary breakthroughs over the long term.

- Objective 3: Demonstrate and communicate the value and impact of the EAR Program and promote opportunities to move from advanced to applied research.

The suite of ABMS research included in the scope of this evaluation addresses all three objectives with an emphasis on objectives 2 and 3. The projects were designed to apply ABMS to transportation modeling and ultimately lead to the methods and techniques that industry, academia, and Government will apply to future projects and research. The evaluation determined the extent to which the projects met this objective and advanced the state of the practice overall.

Given these underlying objectives, the evaluation team developed an analytical framework based on the evaluation areas described in table 1.

**Table 1. Summary of evaluation framework.**

| Evaluation Area | Question by Area |
|---|---|
| Acceleration of the state of the practice, awareness, and knowledge of ABMS approaches in transportation | What were the direct outcomes of the EAR Program–funded ABMS work on the transportation community? |
| Accelerated adoption of and investment in ABMS approaches in transportation | What are the intermediate outcomes relating to research, applications, and continued investment based on the EAR Program–funded ABMS work? |
| Potential impacts of ABMS use | What are the long-term outcomes and impacts of the EAR Program–funded ABMS work expected to be on transportation, particularly in terms of system mobility, reliability, and safety? |

## 1.2 Program Background

This section describes ABMS in context, the timeline of ABMS-related activities conducted by the EAR Program, and the specific activities conducted.

### ABMS for Transportation

During the early to mid-2010s, ABMS gained traction among transportation modelers and researchers. The evaluation team spoke with multiple interviewees who described the evolution of transportation modeling in the following way: The classic transportation model used by most local planning agencies is referred to as a four-step model. The four-step model was developed in the 1950s, is trip-based, and consists of trip generation, trip distribution, mode choice, and route choice.(6) Recently, the model has been improved by using activity-based models (ABMs), which more accurately track traveler movement based on specific activities. These models can be viewed as the demand side of travel modeling.

As ABM usage grew, dynamic-traffic-assignment (DTA) models were developed. DTA models allow for modeling at the corridor and regional levels.(7) In many ways, DTA models represent the supply side of travel modeling, as they focus on transportation networks and systems. Currently, practitioners and agencies are integrating ABM and DTA models into what are referred to as ABM-DTA models. Implementing this integration in practice was a focus of discussion at the 6th Transportation Research Board (TRB) Conference on Innovations in Travel Modeling (ITM), which occurred in May 2016. Interviewees view ABMS as a mechanism for further integrating ABM and DTA models and as the next logical step in transportation modeling.(8)

ABMS has been proven in other disciplines and has now emerged in the field of transportation. Researchers and practitioners have begun integrating its principles into existing traffic models, such as MATSim, PTV Vissim, and DynusT.[(9–11)] An indication of the novelty of the technology is a lack of standard nomenclature.

In addition to the lack of standard nomenclature, confusion also exists regarding what constitutes an agent-based model within the discipline of transportation modeling, for instance, if simply modeling individual drivers or travelers suffices. Several subject-matter experts interviewed by the evaluation team indicated that agent-based models must contain the following attributes:[1]

- The ability of agents to individually remember what happened when they progress from one event to the next or when repeating a certain event. Agents will "learn" from their simulated results and will adjust accordingly during each iteration. For most models, this is reflected in drivers learning from previous incidents or congestion. Eventually, a convergence of choice occurs when agents reach an equilibrium, e.g., drivers deciding on a given route after multiple trial runs with separate options. However, unlike ABMs, in which constraints are applied by the modeler, this convergence is caused by the adaptation and learning of agents. The value of learning and adapting is that agents within ABMS consider their previous actions when making new decisions, as opposed to starting over under new constraints. This mirrors real-world scenarios.

- The ability of agents to use their "memories" in order to adapt and change over time. Much like decisionmakers in a real-world scenario, individual characteristics and values placed on outcomes will vary among agents. The ability to have agents "remember" previous outcomes allows modelers to determine how an individual, e.g., driver or agency, will operate in any given environment. This flexibility of choice and preferences strengthens the overall model and provides planners with more accurate and realistic results on which to base their decisions and recommendations, as they can apply the model to new or different scenarios.

- The ability of agents to interact with each other and their environment. Within agent-based models, an individual's decisions are largely based on his or her interactions with other individuals. For example, drivers make decisions based on the actions of other surrounding drivers. While each agent in a simulation prioritizes preferences, these may change based on how he or she interacts and conflicts with other agents' unique preferences. In an agent-based model, the preferences established by drivers in a traffic-modeling simulation can change, leading to different overall outcomes when the drivers or agents interact.

By incorporating these components, modeling with the aforementioned agents allows for a well-rounded result that gives planners and transportation professionals a more accurate look at possible real-world scenarios without the need to manually apply constraints.

According to one Federal researcher, FHWA and the EAR Program sought to change the paradigms under which transportation models are established by pursuing innovative strategies to tackle common barriers.[2] ABMS has the potential to enhance the state of the practice and has already been proven to be effective by other disciplines, such as economics and ecology.[(12,13)] The same researcher noted that, prior to the EAR Program–funded work, ABMS had been discussed in white papers[3] and various workshops but had not been truly applied to transportation in any setting. As a result, the three EAR Program–funded projects laid the groundwork for all forthcoming research and

[1]Based on phone interviews conducted by Greg Bucci, Michael Green, and Chris Calley (evaluation team), winter of 2016/2017.

[2]Federal researcher, phone interview conducted by Greg Bucci and Michael Green (evaluation team), September 2016.

[3]A white paper is an authoritative report that offers concise information or proposals on an issue.

development on the topic. This researcher explained that the goal of the Driver Behavior in Traffic project was to discover if ABMS was a viable option for modeling driver behavior. Once the Driver Behavior in Traffic project established that ABMS can be applied to transportation in practice, the VASTO and Agent-Based Approach for Integrated Driver and Traveler Behavior Modeling projects were awarded to further explore possible concepts and applications. As a result, the EAR Program–funded research paved the way for use of ABMS in the field of transportation as an advanced form of traffic modeling.

After the EAR Program established the initial viability of ABMS and furthered research on the topic, barriers to development and adoption emerged. Innovative transportation modeling is technical in nature and requires a high level of initial expertise.[4] Thus, reaching practitioners has been a challenge, and maintaining sustained engagement with them has been difficult. This is not because practitioners do not understand the concept of ABMS, but instead because they are not confident that ABMS is currently worth the required investment of cost and time. Metropolitan planning organizations (MPOs) and other agencies already use the four-step model and ABMs, which have proven to be effective. Moving to a new modeling method can be challenging and requires a significant amount of data.[5] Most agencies and MPOs will not adopt a costly and yet-to-be-proven method until it is more widely adopted by other, possibly larger, agencies. Likewise, larger agencies are equally hesitant to be the first to embrace new modeling methods until sufficient validated research and data are available. In short, one interviewee noted the belief that a commercially viable ABMS software model would require a $10 to $20 million investment.[6] These challenges provide context for the current state of ABMS and are further described in this report as they relate to the outcomes and impacts of the EAR Program effort.

Additionally, ABMS has the potential to impact the transportation field beyond the planning models already described. Beyond evolutionary impacts on modeling, ABMS could have a significant impact on related transportation processes. This could specifically include using ABMS to enhance safety countermeasures through the modeling of behavior and user experience and interaction. ABMS could also be used to enhance regulatory permitting processes by providing a better understanding of incentives and how agents would interact given changes to rules and requirements. These impacts remain speculative in nature and, as a result, were not addressed by the EAR Program or within this evaluation.

[4] From the perspective of one subject-matter-expert interviewee, academic researchers are most interested in the subject of ABMS, particularly within the field of transportation. (ABMS researcher, phone interview conducted by Greg Bucci, Michael Green, and Chris Calley (evaluation team), March 2017.)

[5] Federal researcher, phone interview conducted by Greg Bucci and Michael Green (evaluation team), September 2016.

[6] Transportation researcher, phone interview conducted by Greg Bucci, Michael Green, and Chris Calley (evaluation team), January 2017.

## Timeline

Table 2 details a timeline of EAR Program events and activities related to ABMS.

**Table 2. Timeline of events.**

| Date | Program Materials |
|---|---|
| 2009 | Program planning activities (initial stage investigation, solicitation opening, etc.) |
| May 2010 | EAR Program Agent-Based Modeling and Simulation Workshop |
| August 2011 | Trends of Transportation Simulation and Modeling Based on a Selection of Exploratory Advanced Research Projects Workshop |
| February 2012 | Driver Behavior in Traffic project completed |
| September 2013 | Conference on Agent-Based Modeling in Transportation Planning and Operations |
| November 2013 | Primer Report for Agent-Based Simulation and Modeling in Transportation Applications |
| June 2014 | Agent-Based Approach for Integrated Driver and Traveler Behavior Modeling project completed |
| July 2014 | Driver Behavior in Traffic TRL Assessment panel meeting |
| May 2015 | VASTO TRL assessment panel meeting |
| June 2015 | VASTO project completed |
| November 2015 | Agent-Based Approach for Integrated Driver and Traveler Behavior Modeling TRL Assessment panel meeting |

TRL = Technology Readiness Level.

## Project Details

Beginning in 2009, the FHWA EAR Program began investigating the use of ABMS techniques for characterizing driver and traveler behaviors. Part of this investigation included sponsoring a workshop of relevant stakeholders and subject-matter experts in May 2010. The workshop focused on identifying possible applications and challenges of ABMS in transportation as well as discussing existing applications in other disciplines, such as medicine and environmental studies.(14) A second workshop focused on trends in transportation modeling was held in August 2011. Five modeling projects funded by the EAR Program were discussed, including the three ABMS projects.(2) The three ABMS projects, which were awarded based on a competitive bidding process and the recommendations by FHWA staff, were the primary focus of the EAR Program–funded ABMS work and are described in more detail in the following sections.

### *Driver Behavior in Traffic*

The Driver Behavior in Traffic project, awarded in 2009 to Virginia Tech University, aimed to characterize driver behavior using naturalistic driving data and agent-based modeling techniques during both normal and safety-critical driving situations.(15) Existing traffic-analysis and simulation tools could not effectively model a driver's ability to recognize and respond to their environment, such as a traffic incident. This research sought to address that gap. Additionally, the project sought to determine the impact of past experiences on driver behavior. For example, what impact did a previous incident have on a driver?(16) The researchers used PTV Vissim, a traffic-simulation model, to conduct their analysis.(10) The final report from the project was published in December 2012.(14) In addition to the final report, in 2011, the researchers behind Driver Behavior in Traffic wrote a related TRB paper that was published in the *Transportation Research Record* (TRR).(17) While the paper referenced FHWA and staff, the EAR Program was not directly mentioned. In addition to this paper, a list of related publications and presentations produced based on the Driver Behavior in Traffic project can be found in appendix A.1.

### *Evolutionary Agent System for Transportation Outlook*

The VASTO project, awarded in 2011 to the University of Arizona and its coresearchers,[7] builds on the advances made under Driver Behavior in Traffic to further explore ABMS and understand the interactions between travelers, vehicles, traffic-management agencies, and transportation policies.(3) The model developed utilizes computational and algorithmic advances outside the field of transportation and applies those to understanding the complexity of today's transportation systems at a level not currently reached by existing simulation and forecasting methods. In doing so, the model can assist transportation investment decisionmakers, leading to safer, more efficient systems.(18) The VASTO team published two reports that are available on the EAR Program publications website: *A Primer for Agent-Based Simulation and Modeling in Transportation Applications,* published in 2013, and the final project report, *Agent-Based Modeling and Simulation in the Dilemma Zone*, published in 2015.(19,20) Also in 2015, the University of Arizona and George Mason University published another EAR Program–funded report, *Agent En Route Planning, Day-to-Day Learning and Simulation Visualization*.[8] A list of other related publications produced based on the Integrated Driver and Traveler Behavior project can be found in appendix A.2.

### *Agent-Based Approach for Integrated Driver and Traveler Behavior Modeling*

The Agent-Based Approach for Integrated Traveler and Driver Behavior Modeling project was awarded in 2011 to the University of Maryland (UMD) and its coresearchers.[9](4) For the purposes of this report, this project will be referred to as the Integrated Driver and Traveler Behavior project. The goal of the project was to use agent-based modeling to develop innovative methods for improving our understanding of driver and traveler behavior, enhancing transportation systems management, and providing new insights for capital investments.(21) The project sought to meet this goal by developing a transportation planning model that incorporated the behavior of drivers to inform transportation agency decisionmakers. Moreover, this project addresses several technical challenges, including data requirements and needs of ABMS; specification, estimation, and validation of agent behavior; and the software platform developed for model implementation and applications.(19) A list of other related publications produced based on the Integrated Driver and Traveler Behavior project can be found in appendix A.3.

## Additional EAR Program Activities

Upon completion of each project, the EAR Program conducted technology readiness assessment panels. The assessments consisted of presentations from the project teams and independent discussion among subject-matter-expert panelists, who rated the research on a transportation-specific technology readiness scale from 1 to 9. The Technology Readiness Level (TRL) process was generally described in a TRB webinar in April 2016.(22) Appendix B of this report further describes the process. The findings of the TRL assessments for the ABMS projects are described in section 3.1. The ratings for each project are listed in table 3.

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[7]Coresearchers included traffic researchers from George Mason University.

[8]2015 Internal FHWA report by S. Kim, Y. Tian, Y. Chiu, Y. Son, and J. Lien.

[9]Coresearchers included stakeholders from the UMD Department of Civilian and Environmental Engineering, Traffic Operations and Safety Lab, National Center for Smart Growth, Center for Complexity in Business, and the University of Massachusetts Transportation Center and Human Performance Laboratory.

**Table 3. EAR Program ABMS TRL assessments.**

| Project | TRL | Description |
|---|---|---|
| Driver Behavior in Traffic | 2 | Basic research: application formulated |
| VASTO | 4–6 | Applied research: components validated in laboratory environment and evidence of development beginning |
| Integrated Traveler and Driver Behavior | 3 | Basic research: proof of concept |

Along with the TRL assessments, the EAR Program worked with U.S. Department of Transportation's (USDOT's) Volpe Center to develop a general logic model for overall ABMS activities. The logic model was used as a precursor to this evaluation and is presented in section 2.1.

## 1.3 Report Structure

**Section 1** provides an overview of the purpose of the evaluation and a high-level description of the project's history.

**Section 2** describes the evaluation methodology, including data sources, data-collection methods, and data-analysis methods.

**Section 3** summarizes the evaluation's findings.

**Section 4** describes recommendations based on the evaluation's findings.

**Section 5** describes general conclusions drawn from the evaluation. It discusses overarching lessons about the program and summarizes recommendations for FHWA based on the findings of the evaluation.

# 2. Evaluation Design

Using work performed at an earlier stage of the EAR Program ABMS effort, the evaluation team developed an evaluation-specific logic model to trace the activities and outcomes measured by the evaluation (see table 4). This logic model was specifically used to guide the evaluation activities documented in this report. This model, building on work completed prior to this evaluation, then inferred an evaluation approach consisting of three evaluation areas with corresponding questions. The logic model used to guide this specific evaluation is shown in figure 1. The remainder of this section describes the evaluation areas (section 2.1) and evaluation methodology (section 2.3).

## 2.1 Logic Model

A logic model is a logical series of statements that links program components (inputs, activities, outputs, outcomes, and impacts) in a chain of causality. It describes the relationship between program resources, planned activities, and expected results. In general, it is not intended to be a comprehensive or linear description of all program processes and activities, but rather to make explicit how program stakeholders expect program activities to effect change. The logic model helps explain the theories of change that drive the design of a program and provides hypotheses (i.e., if we do this, then this will happen) that can be tested in an evaluation.

**Table 4. ABMS evaluation-specific logic model.**

| Research Inputs | FHWA Research Activities | FHWA Research Outputs | Direct Outcomes (Less Than 1 yr) | Intermediate Outcomes (1–5 yr) | Long-Term Outcomes/Impacts (Over 5 yr) |
|---|---|---|---|---|---|
| • Identified modeling and research needs.<br>• Foundational and conceptual ABMS research from nontransportation disciplines.<br>• Existing literature on characterizing driver behavior.<br>• Federal staff expertise and champions.<br>• FHWA (R&T) funding. | • 2010 workshop on ABMS in transportation.<br>• 2011 workshop on transportation modeling.<br>• Driver Behavior in Traffic project (completed in 2012).<br>• ABMS Primer report (2013).<br>• Integrated Driver and Traveler Behavior project (completed in 2014).<br>• VASTO project (completed in 2015).<br>• TRL panel assessments for each project (2014 and 2015). | • Report on 2010 workshop (published July 2011).[14]<br>• Report on 2011 workshop (published July 2012).[2]<br>• Driver Behavior in Traffic report (2012).[15]<br>• ABMS Primer report (2013).[23]<br>• Integrated Driver and Traveler Behavior report (2014).[4]<br>• VASTO report (2015).[3]<br>• Internal TRL panel reports and results (high-level public presentation in July 2016).[5] | • Increased awareness of ABMS among academic researchers.<br>• Increased collaboration among researchers, planners, and MPOs.<br>• Identification of potential future applications and cross-sector collaboration, such as in energy.<br>• Introduction of ABMS into TRB subcommittees and conference activity. | • Incorporation of ABMS into planning models, such as DynusT.<br>• Improved research tools and processes, including better calibration of models.<br>• Investment in ABMS follow-on research from external sources.<br>• Initial testing of potential future applications, such as modeling automated vehicles with ABMS.<br>• Development of approaches to address adoption barriers, such as model speed, costs, data needs, and the high learning curve of ABMS. | • Utilization of ABMS in transportation policy decisions.<br>• Increased corridor-level management and integration based on ABMS model use.<br>• Use of ABMS models to anticipate the impacts of automated-vehicle technology.<br>• Increased transportation safety based on ABMS model use.<br>• Increased transportation system reliability and capacity based on ABMS model use. |

The primary inputs and activities of the EAR Program–funded ABMS research consist of conducting initial research; providing funding for applied research projects; and tracking, assessing, and documenting those projects. These activities led to research products and reports. Using these outputs as a reference, the evaluation team determined the outcomes and impacts of ABMS in terms of awareness, adoption, and potential impacts on transportation. A particular emphasis, evident through the progression of the logic model, is the role EAR Program funding played in generating outputs that led to tangible outcomes and expected impacts. In other words, how did the EAR Program contribute to the state of the practice of the emerging technology, and what is the potential impact of ABMS moving forward?

## 2.2 Evaluation Areas

Table 5 describes the three evaluation areas.

**Table 5. Evaluation areas and questions.**

| Evaluation Area | Evaluation Questions |
|---|---|
| Acceleration of the state of the practice, awareness, and knowledge of ABMS approaches in transportation | What were the direct outcomes (less than 1 yr) of the EAR Program–funded ABMS work on the transportation community? How did the awareness of ABMS change? |
| Acceleration of adoption and investment in ABMS approaches in transportation | What were the intermediate outcomes (1–5 yr) relating to research, applications, and continued investment, based on the EAR Program–funded ABMS work? How was the work used? |
| Potential impacts of ABMS use | What are the long-term outcomes (over 5 yr) and impacts of the EAR Program–funded ABMS work on transportation? How will system mobility, reliability, and safety be affected? |

## 2.3 Evaluation Methodology

The team evaluated the EAR Program–funded ABMS projects using five data sources. First, the team conducted an online literature review of publicly available information. This review focused on the EAR Program–funded ABMS activities and projects. Second, the evaluation team attended two TRB conferences to explore the current state of the practice for ABMS and identify agent-based research and applications. Third, the team performed website statistical analysis on all EAR Program–published ABMS work using FHWA-produced R&T website log reports. Fourth, the team performed a citation analysis using three robust citation-analysis tools that estimated the impact each project had on the transportation community. Finally, the evaluation team interviewed EAR Program–funded principal investigators (PIs), FHWA subject-matter experts, TRL panelists, and other stakeholders, such as private modeling consultants. The following subsections further describe these data sources.

### Literature Review

The literature assessed focused on relevant ABMS research and reports related to transportation. This generally included an emphasis on EAR Program–funded outputs from projects and workshops as well as the research produced from EAR Program–funded institutions and researchers. These materials are described and cited in section 1.2. In addition, the evaluation team collected and analyzed information on ABMS models and on the state of transportation modeling in general, as referenced in the remainder of this report.

In addition to a basic Internet search, the evaluation team reviewed FHWA and EAR Program websites and searched the Transport Research International Documentation (TRID) database. A transportation research database operated by TRB, TRID is a comprehensive source of transportation-related research and includes articles published via the TRR, the main publication vehicle for TRB.[1]

### Conferences and Presentations

The evaluation team attended presentations at the 95th TRB Annual Meeting and the 6th TRB ITM Conference.(8) The purpose of attending the conferences was twofold. First, the evaluation team assessed the level of interest in ABMS as a method based on the content of presentations and the content of ABMS-related discussion compared to other modeling methods. Second, the evaluation team used the conferences as opportunities to meet with relevant transportation-modeling subject-matter experts, researchers, and consultants and communicate the goals of the evaluation.

Information and perceptions gathered from the conferences were used to inform further research and anecdotally support findings related to the current state of ABMS in transportation. While neither conference directly featured presentations by EAR Program–funded researchers, the 6th TRB ITM Conference included project presentations from the Maricopa Association of Governments (MAG) and from researchers working on the second Strategic Highway Research Program (SHRP2) project C10, Partnership to Develop an Integrated, Advanced Travel Demand Model and a Fine-Grained, Time-Sensitive Network.(24) As detailed in section 3, both projects were influenced by the EAR Program–funded ABMS research.(8)

### Website Statistics Analysis

FHWA has published a series of documents summarizing EAR Program–related ABMS work on the EAR publications list, which is available on the EAR Program's website.(25) The documents include workshop summaries, fact sheets (FSs), and project final reports. Some EAR Program–funded ABMS research is available through the FHWA website, including the reports from the EAR Program–funded workshops. However, only one report from the three projects, the VASTO final report, is available through FHWA. The Driver Behavior in Traffic project report is only available in the National Transportation Library (NTL). The Integrated Driver and Traveler Behavior project report is not publicly available.[2] This significant limitation to report access is further discussed in section 3.1. For the remaining available research, the evaluation team measured how often each document was accessed using FHWA website statistic reports (also described in section 3.1).

Starting in 2016, the FHWA Innovation Management and Communications team has collected a series of website statistics related to the EAR Program website. To do this, the team uses a Web-page-visitor-log analysis tool. The tool uses already-produced log files that include visitation information from the Web server. FHWA produces monthly reports that track the number of times individual users access a given website address. While there are limitations to this analysis, which are described in the following list, the tool allows users to identify and estimate trends and counts related to how often project documents and summary pages are accessed. These values can then be compared to all other project documents and summary pages under the same domain, which in this case is the entire EAR Program portion of the FHWA website.(5)

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[1]TRID combines the Transportation Research Information Services Database and the Organization for Economic Cooperation and Development's Joint Transport Research Centre's International Transport Research Documentation Database.

[2]The evaluation team reached out to the Integrated Driver and Traveler Behavior project report authors and other FHWA staff to obtain a copy of the report.

Limitations of this analysis include the following:

- This analysis is not retroactive, and therefore, past metrics cannot be measured or used for reference.
- One of the metrics the log captures is hits, which are requests to access any file, such as a page or image, usually by clicking on a link. However, a hit by itself does not distinguish who is requesting the information, and therefore, a single user can have multiple hits.
- The log analysis tool measures unique visitors to a website or Web page by Internet provider (IP) addresses. This tool is important for differentiating return users from new users. However, the FHWA reports can double-count users who continue to visit a page multiple times over a short period of time. According to the Web-user guide page, if "a request from an IP address came after some time (timeout) since the last request, it is considered to belong to a different visitor."(26) On average, the timeout parameter is set at 30 min. Therefore, if a user is inactive for more than 30 min and becomes active again, he or she is considered a new user.
- Though informative to some degree, this analysis does not generally capture ABMS awareness or interest more broadly because it compares projects across the EAR Program. For many researchers and practitioners, the EAR Program website is not the primary conduit for this information, and other platforms, such as journals, may provide better insight.

For these reasons, when performing website analysis, it is generally important to view the number of visitors as trending higher or lower and within the proper context, as opposed to as absolute values. Despite these limitations, the website statistics provide a useful background regarding the number of users accessing information related to the EAR Program–funded ABMS projects, particularly in comparison to other EAR Program–funded research. The results of this analysis are primarily described in section 3.1.

### Citation Analysis

The evaluation team conducted a citation, or bibliometric, analysis to estimate how many times the EAR Program–funded ABMS project reports and related publications have contributed to other private and public research. Bibliometrics is the examination of the impact researchers and research products have on other research. To carry out this analysis, the evaluation team measured the number of times published reports, summaries, and FSs have been formally cited or referenced in other published research. Because published works are scattered across a vast and often difficult-to-access network of databases, researchers use search engine tools that can perform broad scholarly literature searches, including what is cited within those works. For the purpose of this evaluation, the team used the following three search engines, which are commonly used in citation analysis research: Google Scholar™, Scopus, and Web of Science.(27–29)

The first tool, Google Scholar™, covers an unspecified list of published works.(27) The types of sources included are books, preprint materials, conference proceedings, working papers, and patents. The next tool, Scopus, searches articles, books, reports, and patents in science, engineering, social science, and arts and humanities, particularly published after 1995.(28) The last tool, Web of Science, searches high-impact science, social science, engineering, and arts and humanities research journals after 1900.(29) One limitation of these tools, however, is that none include the TRR. While the TRR was searched separately for the literature review, it could not be incorporated in the citation analysis.

## Structured Interviews

As table 6 shows, the evaluation team interviewed a number of individuals and groups with some affiliation to the EAR Program–funded ABMS projects. The interviews were wide ranging and covered all relevant evaluation areas. Interviewees were asked to describe their awareness of the EAR Program–funded work, including their thoughts on the TRL assessments if they participated. Interviewees were also asked to assess where ABMS fits within the current state of transportation modeling, including the advantages and disadvantages of ABMS and the possible barriers that would prevent further deployment.

**Table 6. Interviewees.**

| Interviewee | Role | Interviewee Category |
|---|---|---|
| Atlanta Regional Commission | Model users, TRL panelists | Industry researcher |
| Argonne National Laboratory | Subject-matter experts | Federal researcher |
| FHWA | Project initiators, TRL panelists | Federal researcher |
| National Renewable Energy Laboratory | Subject-matter experts | Federal researcher |
| Major transport and infrastructure firm | Practitioners, subject-matter experts | Industry researcher |
| UMD | EAR Program–funded researchers | Academic researcher |
| University of Texas at Austin | Subject-matter experts | Academic researcher |
| Virginia Tech University | EAR Program–funded researchers | Academic researcher |

Interviewees were asked a general set of questions about their understanding of how ABMS was used within the context of transportation. After establishing this information, they were asked how they felt the EAR Program–funded work impacted ABMS. Last, interviewees were asked how they saw ABMS evolving and its potential to be applied to transportation-related challenges in the future. Responses and followup questions varied by interviewee.

The specific questions were tailored for each interviewee. For example, if an interviewee was a TRL panelist, a portion of the interview was dedicated to discussing and reflecting on the panel on which he or she served.

The team assured all interviewees that their identities would remain confidential in order to achieve unbiased answers to interview questions. Throughout the document, when interviewees are quoted, the evaluation team noted the month and year of the interview as well as the interviewer, but the interviewee name has been redacted. To maintain continuity and comparability between interviewee responses, a generic title was attributed to each interviewee.

# 3. Evaluation Findings

This section is divided into the three evaluation areas examined by the evaluation team. Each section assesses the evaluation area at a high level and then follows with an indepth discussion of findings. Findings are supported by evidence collected through the evaluation methods described in section 2.3.

## 3.1 Awareness of ABMS in Transportation

The EAR Program and the EAR Program–funded researchers brought awareness of ABMS into transportation by being among the first to investigate agent-based modeling within the field of transportation. This is indicative of the fact that the EAR Program researchers chose to label the method "ABMS" (as it relates to transportation). While the transportation community interested in ABMS was not universally aware that the EAR Program directly funded ABMS research, subject-matter experts and researchers are familiar with the work that was funded and with the researchers who conducted the work. The EAR Program–funded PIs remained active in the discipline after the completion of their EAR-funded projects. Ultimately, the EAR Program–funded research enhanced awareness and the state of the practice by effectively demonstrating the application of ABMS in transportation.

### Detailed Findings

| Finding: The EAR Program–funded research enhanced ABMS research by establishing its applicability and viability for transportation. |
|---|

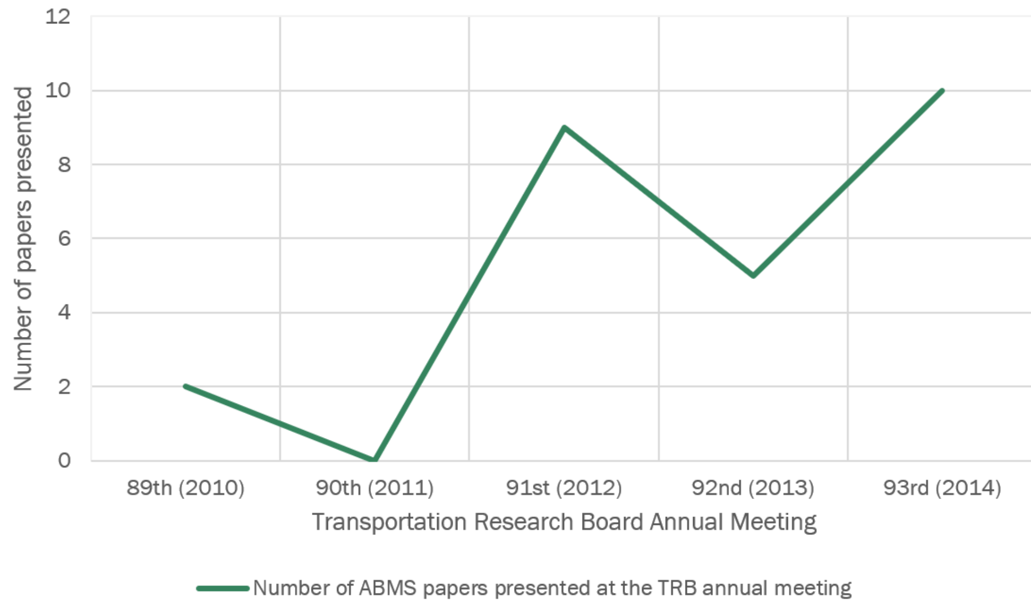
The EAR Program was established to fund breakthrough research that has a higher risk associated with it in the hopes that it will provide long-term solutions to transportation systems.(5) The EAR Program's funding of innovative research has allowed new methods like ABMS to gain traction within the field of transportation. Some innovative tools, once developed, will largely be used by public agencies that do not have the funds to invest in their development. As a result, those tools rely heavily on Federal funding, provided by entities such as the EAR Program, to make the transition from a conceptual phase to a promising research topic. In a question about the transportation community and the potential for private industry to move transportation modeling forward, one interviewee responded with the following:

> *"Federal people need to recognize [the small market and complex nature of the transportation community] and invest in travel models. It is important for decisionmaking, and it needs to be subsidized. We have something today but not at a professional level."*[1]

Prior to EAR Program funding, ABMS was largely unknown within the transportation community (figure 1). Currently, ABMS is a topic of great interest among transportation researchers, in part based on the EAR Program's efforts. While ABMS is still developing as a practical tool for State and local transportation agencies, without the EAR Program effort, it would have likely remained a theoretical possibility explored in academia rather than put into practice or applied in the near term.

[1] Transportation researcher, phone interview conducted by Greg Bucci, Michael Green, and Chris Calley (evaluation team), January 2017.

Representation of ABMS at TRB annual meetings has grown steadily since the EAR Program–funded efforts began.(30) While there is no direct evidence linking the EAR Program to the growing interest in ABMS solutions in transportation, it is reasonable to infer that the EAR Program effort, which began in earnest in 2010 and began producing output in 2011, contributed to the technique's growth by establishing applicability. Figure 1 shows the count of TRB annual meeting papers focusing on ABMS over time.




Source: FHWA.

**Figure 1. Graph. ABMS papers presented at TRB annual meetings.(30)**

Along with funding three ABMS-related projects, the EAR Program also conducted retrospective TRL assessments for each. These assessments were used as measures of effectiveness to inform this evaluation. Each assessment occurred approximately 1 yr after the research concluded and consisted of a half-day meeting with five panel members. Panel members represented academia, Federal and local Government, and private industry. The PIs presented their projects, and the panel members then discussed and rated the research. A full description of the TRL process and rating levels, which range from 1 to 9, can be found in appendix B. The ratings received for each of the ABMS projects are described in section 1.2 (table 3).

At the time the research was conducted and shortly thereafter, as the TRL ratings indicate, ABMS methods and techniques were still focused on basic research. The projects explored were not yet ready for development or application. However, this was not an indication that the EAR Program–funded projects did not advance the technology. To the contrary, interviewees indicated that investing in basic and applied research was precisely the role of the EAR Program, and the EAR Program investment has helped to further develop the use of ABMS in transportation.[2] One TRL

[2]Based on interviews conducted with ABMS stakeholders, phone interviews conducted by Greg Bucci, Michael Green, and Chris Calley (evaluation team), 2016–2017.

panelist noted that serving on the panel provided an introduction to ABMS, indicating the state of ABMS at the time.[3]

As described in section 1.2, one Federal researcher interviewed noted that, prior to the EAR Program–funded work, ABMS had not been applied to transportation in any setting.[4] As a result, the EAR Program–funded projects laid the groundwork for all forthcoming research and development. This finding is reinforced by the TRL ratings. The EAR Program–funded research projects and related activities developed ABMS within the field of transportation from an effective TRL rating of 0 (i.e., not registering on the TRL scale, which starts at 1) to the 2 to 4 range where it currently resides.

The evaluation team found limited evidence of ABMS transportation research prior to 2009, when the EAR Program effort began. A 2004 article in the TRR coauthored by Lei Zhang, the PI for the Integrated Traveler and Driver Behavior project, appears to describe a first attempt at applying ABMS to travel-demand modeling.(31) In the late 2000s, Zhang and various coauthors conducted agent-based work on price competition in congested networks as well as transportation and land use.(32,33) Additional examples of later research applied ABMS to a pedestrian landuse model and a marketplace penetration model for plug-in hybrid electric vehicles.(34)

Based on the limited exploratory research applying ABMS to transportation models in the late 2000s, it is clear that the EAR Program investment advanced the state of transportation-related ABMS research by establishing its viability. This finding is reinforced by the TRL ratings of the three projects.

Finding: The EAR Program–funded research contributed to the progression of transportation modeling toward ABMS.

Practitioners and subject-matter experts interviewed noted that one way to integrate ABM-DTA models is through ABMS. As a result, interviewees believe that ABMS is the next step in the progression of transportation modeling and forecasting.[5]

As interest in ABMS has increased in recent years, applications and research tools have been developed both to test ABMS in transportation settings and to begin developing models. While exploratory in nature, two of the three EAR Program–funded projects led to research tools being developed and used by local and State agencies. MAG, the council of Governments in the Greater Phoenix region, is using portions of the VASTO research from the University of Arizona.(35) The Maryland State Highway Administration (SHA) and the Baltimore Metropolitan Council (BMC) have used portions of the Integrated Traveler and Driver Behavior research. These activities are described in more detail in section 3.2.

In addition to the specific uses of the EAR Program–funded research by MAG, the Maryland SHA, and the BMC, it is clear that ABMS usage and interest has grown in recent years. While the methods remain under development in many cases, implementations have been observed, and further ABMS research has been conducted in the mid-2010s (as can be seen in figure 1). This includes usage of

[3]Federal researcher, phone interview conducted by Greg Bucci and Michael Green (evaluation team), September 2016.

[4]Federal researcher, phone interview conducted by Greg Bucci, Michael Green, and Chris Calley (evaluation team), February 2017.

[5]Transportation researcher, phone interview conducted by Greg Bucci, Michael Green, and Chris Calley (evaluation team), January 2017.

prototype applications developed by researchers with the Department of Energy (DOE), further described under the next finding.

Based on the current state of ABMS and the progression of transportation modeling in general, the EAR Program and the three EAR Program–funded research projects in particular have contributed to the advancement of ABMS within the field of transportation. The EAR Program–funded projects have shown the viability of ABMS and have led to implementations in specific cases. The full magnitude of that contribution will be determined in the future as ABMS methods continue to be developed and implemented by transportation researchers and practitioners.

Finding: EAR Program–funded studies have contributed to collaboration in the development of transportation-modeling software, particularly between DOE and USDOT.

Overall, there is limited evidence of independent followup work that was directly related to the EAR Program–funded research. However, it may still be early, as model development and shifts in research typically occur slowly in this field. As time progresses, followup work that is specifically reliant on the EAR Program–funded research may develop.

However, some partnerships developed through the EAR Program–funded work were still carried on following project completion. Other partnerships were also formed indirectly through project PIs or work that was influenced by the EAR Program–funded research.

An informal partnership mentioned during multiple stakeholder interviews is between DOE and USDOT. Collaboration between DOE and USDOT in transportation simulation can be traced back to earlier work that is similar in nature to ABMS, known as the Transportation Analysis and Simulation System (TRANSIMS). TRANSIMS was one of the first successful codeveloped applications that produced travel forecasts, planning, and emissions analyses. More recently, there have been efforts initiated by DOE that involve researchers directly connected to the EAR Program–funded work. In November 2016, DOE hosted a symposium entitled SMART Mobility, Modeling, and Simulation Tools: Practice, Challenges, and Future Directions.(36) Researchers from the VASTO and Integrated Traveler and Driver Behavior projects delivered presentations related to ABMS. Additionally, TRL panelists presented on modeling applications with agent-based elements.

The Integrated Driver and Traveler Behavior project used an existing framework for its ABMS model that has also historically been adopted by other disciplines or groups, such as DOE. The framework, named Polaris, “is a high-performance, open-source agent-based modeling framework designed to simulate large-scale transportation systems.”(37) It was developed by FHWA and DOE’s Argonne National Laboratory with the intent to demonstrate how an agent-based framework can be adopted and implemented by a planning agency. A prototype of the model was first built for the city of Chicago, IL, which has since worked with Northwestern University and a contractor on other transportation models with agent-based elements.(38) The Chicago Polaris prototype was meant to demonstrate how travel modeling can be done efficiently using this type of framework. Polaris has also been used to develop transportation models for the cities of Detroit and Beijing with the help of the University of Illinois and the University of Beijing.

More generally, following the completion of the EAR Program projects, there were initial attempts at promoting further collaboration between the project researchers and others in the transportation community. In 2015, FHWA project leads and the three project PIs met at the 94th annual TRB conference to discuss next steps for research. One of the goals of this meeting was to establish an advisory committee consisting of these individuals and others from academia and the transportation-modeling industry. While the committee was not developed, there still remains interest among stakeholders for this type of collaboration.

Independently, researchers and practitioners involved with the three ABMS studies have continued to work on transportation-related cross-sector ABMS activities, indicating the success of the initial EAR Program funding. In addition to the TRB meeting in 2015, EAR Program PIs, FHWA staff, other researchers, and practitioners were expected to participate in a symposium that discussed the challenges and opportunities related to ABMS within the field of transportation.[6] The symposium effort, which was led by FHWA at the time, eventually lost momentum due to personnel changes, including a key coordinator at FHWA. Currently, a Federal or academic champion is needed to continue to promote and oversee the development of ABMS-related research and models.

Finding: Users access EAR Program ABMS-related publications at a rate consistent with that of the ABMS Primer, which is one of the most visited publications on the EAR Program website.

To determine if the EAR Program–funded research increased awareness and knowledge of ABMS for transportation applications, the evaluation team used the FHWA reports to analyze website activity related to FHWA ABMS research. The team focused on reports available on FHWA's EAR Program website domain. The results of this analysis, which can are available in table 7, are displayed in an average monthly format for the following EAR Program ABMS publications:

- *Modeling Driver Characteristics—Driver Behavior In Traffic* (Driver Behavior FS).(16)
- *Modeling Complex Behaviors and Interactions—New Methods to Assist Decisionmaking and System Operations* (VASTO FS).(18)
- *Agent-Based Modeling and Simulation in the Dilemma Zone* (VASTO report).(20)
- *A Primer for Agent-Based Simulation and Modeling in Transportation Applications* (primer).(23)
- *Agent-Based Modeling and Simulation Workshop Summary Report* (2010 Workshop).(14)
- *Trends of Transportation Simulation and Modeling Based on a Selection of Exploratory Advanced Research Projects: Workshop Summary Report* (2012 Workshop).(2)

In some cases, the publications are available in Hypertext Markup Language (HTML) format, while in other cases, they are available as a Portable Document Format (PDF); therefore, both types of downloads are shown in table 7. The reports also summarize all visitors to any page within a publication directory and all subdirectories or files.[7] Based on the reporting format used by FHWA, directory statistics are included in a report only if the directory is within the top 50 directories visited under the Advanced Research Web domain.[8] The benefit of using directory website statistics is that all activity related to a publication is recorded, including viewing HTML pages directly in a Web

[6]Federal researcher, phone interview conducted by Greg Bucci, Michael Green, and Chris Calley (evaluation team), January 2017.

[7]A directory refers to the Web page address under which all subdirectories or files are located. For example, https://www.fhwa.dot.gov/advancedresearch/pubs/15082/ is the directory, and https://www.fhwa.dot.gov/advancedresearch/pubs/15082/005.cfm is the subdirectory.

[8]From March to May 2016, only the top 20 directories were listed on FHWA's reports. Beginning in June 2016, FHWA started listing the top 50 directories.

browser or PDF downloads. The biggest limitation with this analysis, however, is that because only the top 50 directories are listed, there are missing statistics for directories with comparatively fewer visitors. The directory statistics can also be seen in table 7.

**Table 7. Average monthly website visits for EAR Program ABMS-related publications.[9]**

| Type of Web Page Visits | Publication Title Page Visits | Publication PDF Downloads | ABMS Publication Directory Visits |
|---|---|---|---|
| Driver Behavior FS | 65 | -- | -- |
| VASTO FS | 64 | 42 | 149 |
| VASTO report | 69 | 60 | 160 |
| Primer | 79 | 387 | 731 |
| Workshop 2010 | 85 | 49 | 138 |
| Workshop 2012 | 94 | 42 | 139 |

–Web pages that did not have any associated data because they were not within the top 50 visited directories under the EAR Program.

Overall, users continue to access all six publications at similar rates, albeit in different formats. Because there is only a year's worth of data available for analysis, it is difficult to identify clear trends for any particular publication. One clear result, however, is the user activity for the ABMS Primer.(23) Since January 2016, in every month except one, the Primer has been the most downloaded PDF under the EAR Program website domain. This indicates the interest in ABMS research compared to other EAR Program–funded activities. Notably, comparing visits within the EAR Program website alone does not speak to the broader awareness of EAR-researched ideas and methods. In order to gain that understanding, qualitative perceptions of subject-matter experts and broader literature and citation searches are required. Those areas are also explored within this evaluation.

Finding: ABMS EAR Program–funded research at large has not been suitably published, making materials difficult to locate online. Additionally, the EAR Program website domain does not fully capture all ABMS EAR Program–funded work and is therefore a limited resource.

As further described in the recommendations of this evaluation (section 4), one of the evaluation team's main findings is that two of the final project reports, Driver Behavior in Traffic and Integrated Driver and Traveler Behavior, are currently not available for download on FHWA's EAR Program website domain. Additionally, an EAR Program–funded report addressing portions of the VASTO work is also not available on the EAR Program website.

Without access to the studies and reports, researchers and practitioners cannot use FHWA's website as a resource for ABMS, and the studies cannot be leveraged by the agency to draw attention to the EAR Program's overall effort. While researchers may be likely to access EAR Program–funded outputs via other platforms, such as academic journals or the NTL, posting or linking to results on the FHWA or EAR website would highlight the research funded by the Government. Additionally, because the publications are not hosted on FHWA's website servers, it is not possible to track website statistics related to these reports.

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[9]Average values include all months from January 2016 to January 2017 under which visits were recorded. In some cases, monthly values were not recorded because the website log report only captured top listing groups, and a specific report did not fall within that group. Additionally, FHWA's log reports did not record any website statistics for the month of February 2016.

Finding: Work performed by the three EAR Program–funded projects promoted ABMS; however, the EAR Program was not widely acknowledged for encouraging awareness of ABMS. This represents a missed opportunity to acknowledge the contribution of an important FHWA program.

In addition to the website statistical analysis, the evaluation team performed a literature review and indepth interviews to understand the effect EAR Program–funded research has had on the state of the practice of ABMS. While difficult to link the EAR Program–funded research directly to awareness of ABMS, the researchers funded by the EAR Program were well known among interviewees. Prior to the EAR Program–funded work, ABMS did not have a strong presence in the transportation-modeling discipline (both domestically and internationally) and was only used in other disciplines. Economists have used ABMS in game theory simulations, and forms of ABMS have aided ecologists in computational modeling since 1987.(12) Yet, since 2010, when the three EAR Program–funded projects began, awareness and knowledge of ABMS has grown within the transportation-modeling discipline.

ABMS awareness has risen more among academic researchers as compared to practitioners. One interviewee noted this fact and the overall awareness of ABMS as follows:

> *"Academics and students are interested mostly. We have had trouble reaching the practitioners .... People are afraid to jump in until there is a real commitment from above, sponsoring agencies, really .... If you said ABMS in the past, people used to say, what is that? But now, people are aware of it. Maybe they don't know the details, but they are aware of it."*[10]

Although the EAR Program itself did not gain notable exposure from funding ABMS, the projects developed from the EAR Program–funded research were known in communities historically outside of transportation disciplines. For example, an engineer working with DOE started a committee with one of the three EAR Program–funded PIs to establish a collaborative effort in overcoming difficulties the transportation-modeling community faced. DOE has become progressively more interested in electric vehicle usage and user choices regarding charging stations and routes. While research is ongoing, DOE hopes to understand how agents will modify their behavior to account for the additional variable of a charging station added to their travel routes.

Finding: Interest has been limited by the resources and funding necessary to implement ABMS as a traffic-modeling solution in practice.

ABMS has potential to improve and advance transportation modeling. However, due to the limited number of current deployments and implementations, significant further research and advancement is required for this potential to be realized. This has hindered interest in the technique.

Transportation experts prototyping ABMS technology noted significant computational breakthroughs in recent years but predict that running ABMS in real time will require systems to operate at 200 times their current computing speed.[11] Such technological requirements create a cost burden that smaller MPOs cannot sustain. However, third-party providers have begun offering computing infrastructure as a service. This type of service provides the capabilities of advanced expensive hardware, such as computing speed, for a cost-effective rental fee.(39) The service can be rented by

[10]Transportation researcher, phone interview conducted by Greg Bucci, Michael Green, and Chris Calley (evaluation team), January 2017.

[11]Based on an internal conversation with UMD researchers.

users via an online cloud-based system that requires them to purchase their own capital assets. As these services become more refined, users may have a greater ability to develop ABMS models.

Outside raw computing power, one interviewee noted a need for a transportation-modeling "language" specifically for ABMS.[12] Unless, as noted by this same interviewee, the computer science discipline develops a more effective way to run these models, this will remain a barrier to ABMS dissemination and potential.

Transportation modeling is inherently complex. One interviewee was open about this concern and noted the following:

> *"There is a challenge in communicating the basis of how they come up with these [modeling] projections now. And, when you throw ABMS lingo on top of it? It gets even more difficult and hard to understand what's going on."*[13]

Compounding these technological and technical barriers, interviewees noted that ABMS is currently expensive to implement. When agencies and MPOs consider the application of new technology, return on investment is generally a priority. Due to the risks associated with employing new resource-intensive technologies, ABMS is not currently among the first choice for agencies when they are seeking immediate modeling solutions. Without a proven history of practical results, interest in ABMS is still largely in the testing phase and not yet ready for widespread use.

Funding new types of research in transportation modeling does not always produce an immediate result. This can limit overall interest in certain modeling techniques. One Federal interviewee noted the trouble with new types of modeling:

> *"One of the challenges in the modeling and simulation industry is convincing new users to use the new model and improving the ease of use. In other words, the challenge is user specific. There is a big learning curve to adopt a new model, and it might be very resource intensive."*[14]

Findings: Without additional Federal funding to support emerging ABMS applications, such as within transportation modeling, it is unlikely that ABMS will be widely adopted or implemented.

ABMS was described regularly by interviewees as a resource-intensive and difficult-to-understand technique. Therefore, while ABMS awareness has grown in the transportation community, its availability as a usable tool has progressed slowly. Despite those barriers, transportation professionals who are aware of the potential of ABMS are both hopeful for its future and thankful for EAR Program–funded support. Interviewees believed that, by funding initial research, the EAR Program contributed to the advancement of ABMS, allowing this next phase of barriers to be addressed.

As previously noted, it is difficult to make large-scale financial investments without adequate return on investment. Theoretical innovations like ABMS are difficult to commit to from the standpoint of

[12] Transportation researcher, phone interview conducted by Greg Bucci, Michael Green, and Chris Calley (evaluation team), January 2017.

[13] Federal researcher, phone interview conducted by Greg Bucci, Michael Green, and Chris Calley (evaluation team), January 2017.

[14] Federal researcher, phone interview conducted by Greg Bucci and Michael Green (evaluation team), September 2016.

the private industry without a clear picture of adequate net revenue upon completion of research. One EAR Program–funded PI had the following perspective on the EAR Program–funded research and the future of ABMS:

> *"I wish more sponsoring agencies could do something similar. That's really how we can do a paradigm shift and break out. That's what I see as EAR's real value. Now, we can always refer to the project [we did] and show that with the right funding we can have really good results."*[15]

Federal funding through the EAR Program and others is essential in breaking down barriers to discover new technologies, particularly in disciplines that rely on public funds, such as transportation. The market for transportation modeling is small, but the demand is large, so the potential for publicly funded research to have a widespread impact on agencies and users is clear. One EAR Program–funded PI noted how difficult it is to conduct groundbreaking and innovative research that has not previously had traction. This PI voiced the difficulty in funding such research and said the following:

> *"A lot of time when we are interested in something that we think has a lot of merit .... Having a sponsored project with the [USDOT], for example. We will do it beyond the requirement, sometimes on our own time, just to get something interesting going. It's hard to sell those meritorious ideas that are breaking a new paradigm, with, for example ... traditional funding."*[16]

# 3.2 Adoption of ABMS in Transportation

In terms of ABMS adoption and investment, the EAR Program–funded research has directly led the transportation community to become more interested in expedient and effective ways to model drivers' behavior in real-world settings by utilizing realistic decisionmaking techniques. Several MPOs and other entities have begun working with EAR Program–funded researchers to implement ABMS tools and methods.

## Detailed Findings

| Finding: There are few to no citations of the EAR Program–funded ABMS projects in other research. |
|---|

Using the three citation analysis search tools described in section 2.3, a snapshot displaying citations of the EAR Program–funded work can be seen in table 8.

[15]Transportation researcher, phone interview conducted by Greg Bucci, Michael Green, and Chris Calley (evaluation team) in January 2017.

[16]Transportation researcher, phone interview conducted by Greg Bucci, Michael Green, and Chris Calley (evaluation team), January 2017.

**Table 8. Citation analysis results.**

| Search Terms | Document Type | Google Scholar™ | Web of Science | Scopus |
|---|---|---|---|---|
| Driver Behavior in Traffic | Report | 0 | 0 | 0 |
| Agent-Based Approach for Integrated Driver and Traveler Behavior Modeling: Theory, Methodology, and Applications to Transportation Systems Management and Investment Planning | Report | 1 | 0 | 0 |
| Agent-Based Modeling and Simulation in the Dilemma Zone | Report | 1 | 0 | 0 |
| Agent en Route Planning, Day-to-Day Learning, and Simulation Visualization | Report | 0 | 0 | 0 |
| Agent-Based Modeling and Simulation Workshop | Workshop | 0 | 0 | 0 |
| Trends of Transportation Simulation and Modeling Based on a Selection of Exploratory Advanced Research Projects | Workshop | 0 | 0 | 0 |
| A Primer for Agent-Based Simulation and Modeling in Transportation Applications | Primer | 7 | 0 | 0 |

The main finding from the citation analysis is that the EAR Program–funded ABMS research and products are not well cited by the general research community. Notably, followup articles and papers written by EAR Program–funded PIs do not cite the corresponding final reports. In addition to limited online availability for some EAR Program–funded research products, adoption and usage of the EAR Program–funded ABMS research is currently low. There are several possible reasons for this. First, more time may be needed for citations and followup research to be published; interviewees indicated that academic researchers are currently exploring ABMS.[17] As a result, more time may be needed for publication, and references to the EAR Program–funded work, to occur. Second, while the final reports may not be valuable for researchers, the additional followup journal articles and papers produced by the PIs are cited with greater frequency. A detailed summary of all followup works and number of citations can be seen in appendix A. While the followup articles do not directly cite the EAR Program–funded final reports, each PI has indicated that the EAR Program–funded work was influential in the development of each followup work. Finally, evidence suggests that, while there are several entities and agencies specifically advancing ABMS, the technology is not yet widespread. As a result, this broad citation analysis, which uses tools that broadly encompass the arts and sciences but do not include the TRR, may not be the most illustrative way to describe current activity.

Targeted followup presentations or promoting practical applications of the research could enhance its visibility and lead to increased citations. These concepts are further described in section 4.

Finding: The EAR Program–funded research successfully generated ABMS usage through new research tools in Arizona and Maryland.

Despite the lack of citations, within the first several years of completing the EAR Program–funded projects, multiple followup efforts have emerged. These efforts include new partnerships, additional agent-based academic research published, and presentations at conferences and meetings.

[17]Transportation researcher, phone interview conducted by Greg Bucci, Michael Green, and Chris Calley (evaluation team), January 2017.

The Integrated Traveler and Driver Behavior research, developed by UMD, has led to additional FHWA-funded research through SHRP2 project C10: Partnership to Develop an Integrated, Advanced Travel Demand Model and a Fine-Grained, Time-Sensitive Network.(24) The C10 project is a part of the Capacity focus area of SHRP2. The Capacity focus area's goal is to develop approaches and tools for systematically integrating economic, environmental, and community requirements into the analysis, planning, and design of new highway capacity.(40) C10 has one of the specific objectives of making an operational advanced travel-demand model and time-sensitive network. This integrated model system is a key component because most current travel models do not have the potential to balance the relationship between traveler behavior and network conditions. Current models also do not have the capability of inputting the effects of innovative transportation policies, such as variable road pricing.(41) The project implemented the ABMS approach for integrated traveler- and driver-behavior modeling by directly incorporating the improved run times developed by the EAR Program–funded project into the travel-behavior models used in the C10 project.

While conducting this work, in order to address common data constraints for smaller planning agencies, UMD worked with agencies and local Governments using survey data for advanced behavioral modeling. UMD applied its model, which was built for the Baltimore area, and recalibrated it for different locations. Currently, the ABMS model is being implemented into the models used by the Maryland SHA and the BMC. UMD hopes to eventually transfer the ABMS model to other cities, MPOs, and transportation agencies.

In addition to the C10 project, UMD has used elements of ABMS in their effort to study the impact of the Washington Metropolitan Area Transit Authority SafeTrack plan. UMD has also received a $4 million grant from DOE's Advanced Research Projects Agency–Energy to incorporate ABMS into an energy optimization model.(41)

Researchers at UMD have published numerous papers relating to ABMS and its applications. In a conversation with researchers from UMD, the evaluation team learned that UMD published 12 papers following up on the EAR Program–funded work and its applications. Papers were published in TRR and the American Society of Civil Engineers's *Journal of Urban Planning and Development* and *Journal of Transportation Engineering* (see appendix A for the full listing).(42) UMD researchers have also presented at over 20 different conferences and workshops. This work has led to further funding from other agencies to support more ABMS initiatives, such as a grant from the DOE, which is further described in section 3.3.[18]

Along with the SHRP2 work performed by UMD, VASTO, which was developed by the University of Arizona and George Mason University, is based on the DTA model known as DynusT.(11) The VASTO research has been implemented and is being used by MAG. As is often the case for local MPOs and councils of Government, MAG worked with a consultant to develop its planning models and decided to move forward with ABMS.

**Finding: Interest in ABMS has led to increased research within academia and Government settings.**

Students and researchers at universities are seeing the theoretical potential of ABMS and are increasingly researching the wide range of possibilities it has to offer. Interviewees anecdotally mentioned that various traffic-modeling tools are integrating ABMS features within their models by taking the introductory steps of simulating unique agents within large and detailed networks. While

[18]Based on evaluation team email correspondence with UMD on May 15, 2017.

ABMS is currently being implemented in only a small number of practical ways, the wide-ranging real-world applications are spurring innovation in the transportation community.

Although the transportation community is small, collaboration exists with local transportation agencies and researchers, such as work done in Chicago with the Chicago Transit Authority and Northwestern University.(43) As noted above, the University of Arizona's EAR Program–funded project led to a collaboration with MAG. MAG noted that understanding how motorists interact would allow them to implement strategies that would promote safer decisionmaking in driver behavior. The increased awareness of ABMS and the availability of new tools in a research environment means that universities across the country will have graduate students experimenting with new ways to improve the practice of modeling. A DOE researcher, who said the following, sees the future of ABMS being pushed by students who specialize in these sorts of tools:

> *"Current new graduates are cutting their teeth on tools like MATSim to generate trip matrices for synthetic populations, so I imagine in 5 to 10 years, ABMS systems will be state of the art, state of the practice, because most MPOs will have filtered them into day-to-day operations."*[19]

One practitioner interviewed is heavily involved in the research community and very interested in furthering the state of the practice of ABMS.[20] This interviewee has been in multiple discussions with municipalities trying to learn what it would take to practically implement ABMS in transportation modeling. This practitioner perceives the largest issue to be funding, as effective types of ABMS will require high-level programming and large amounts of data storage, both of which can traditionally amount to millions of dollars. By providing public funding to further the state of the practice and break down the barriers of investment, the EAR Program has significantly contributed to the development in this area. As noted in section 3.1, without public funding, developing innovative concepts to advance transportation modeling would be difficult.

An example of MPO engagement with EAR Program–related ABMS work is the Atlanta Regional Commission (ARC). Over time, ARC has transitioned from the traditional four-step model to the ABM.(44) The MPO's goal is to gradually transition toward a more complete ABMS adoption. With this effort in mind, and similar to MAG in Arizona, ARC has been using DynusT, which will allow the agency to eventually incorporate agent-based modeling characteristics into existing transportation models.(45) The VASTO research is now an open-source platform, which allows ARC and others to potentially build on their current models. While this has not been undertaken yet, there is an opportunity for future developments to stem from the EAR Program–funded work.

In terms of other usage of ABMS, beyond projects directly related to the EAR Program–funded work, there is evidence of continued research and development through other FHWA projects. These include the previously mentioned Polaris model as well as various SHPR2 research efforts that are incorporating ABMS, specifically Incorporating Performance Measures in Planning and Operations Modeling Tools (project L04) and Improving Our Understanding of How Highway Congestion and Pricing Affect Travel Demand (project C04).(46,47) While these projects are not directly related to the EAR Program–funded work, clear overlap exists based on the involvement of FHWA subject-matter experts across projects.

[19]Federal researcher, phone interview conducted by Greg Bucci, Michael Green, and Chris Calley (evaluation team), March 2017.

[20]Federal researcher, phone interview conducted by Greg Bucci and Michael Green (evaluation team), September 2016.

Based on the above examples as well as the general sense from interviewees that ABMS is growing as a technique, it is clear that formal consideration of the technique as it applies to transportation models is beginning to occur among agencies.

Finding: Private industry is looking toward ABMS as a practical solution to address issues State and local transportation agencies face with current modeling tools.

As previously described, ABMS was largely unknown in the transportation community prior to the EAR Program's activities. While ABMs were based on user choice, these models lack the evolutionary capabilities of ABMS. The ability provided by ABMS to create individual actors that learn and develop new opinions over time, based on separate choices, offered a unique way to advance transportation modeling.

Generally, private contractors work with State and local transportation agencies to develop more effective ways to relieve congestion and improve flow, often utilizing traffic-modeling tools. Industry practitioners are not always included in the research that occurs at the university level or within Federal laboratories, but those interested in the practice follow research developments closely.

A former FHWA employee who assisted in the EAR Program–funded research of ABMS relayed a recent conversation with a private developer who was interested in ABMS.[21] The developer noted that their company is now integrating ABMS into their modeling software package. The transportation community working on developing new modeling techniques is moderately sized, but there is burgeoning interest in practical application of these new models. Industry professionals see a strong future in ABMS.

Products and models such as MATSim, PTV Vissim, DynusT, and Polaris are already incorporating aspects of ABMS.(9–11,37) These new and updated traffic-simulation models have the potential to "simulate whole days within minutes" as well as "simulate millions of agents or huge, detailed networks."(9) Through its incorporation, ABMS is contributing to the evolution of transportation modeling, allowing agencies greater flexibility and accuracy in their modeling approaches and validation. This will, in turn, lead to better models overall and more effective transportation solutions.

## 3.3 Impacts of ABMS Use

Researchers and practitioners have speculated on a wide range of possibilities in which ABMS can enhance transportation mobility, reliability, and safety. Notably, researchers believe ABMS is the next logical step in transportation modeling and has the ability to improve the efficiency and consistency of transportation models as well as address transportation network issues in real time.[22] However, ABMS is yet to be adopted on a wide scale, and the impacts of its usage are yet to be realized. While not an indication that the EAR Program–funded projects did not fulfill their goals, this finding is informative for future work and has several possible causes. As described in section 1.2, ABMS in general faces barriers in terms of costs and the development of technical expertise and technological capabilities. Given the maturity of the EAR Program–funded research results, specifically in terms of the TRL scale, broad adoption at this stage was not expected. However, the

[21]Transportation researcher, phone interview conducted by Greg Bucci, Michael Green, and Chris Calley (evaluation team), January 2017.

[22]Transportation researcher, phone interview conducted by Greg Bucci, Michael Green, and Chris Calley (evaluation team), January 2017.

EAR Program–funded projects in particular could have benefited from a more comprehensive or centrally driven outreach and publication effort.

## Detailed Findings

Finding: ABMS has not been adopted or deployed on a broad level; however, potential new applications for ABMS exist.

As described in sections 3.1 and 3.2, there is evidence that users and practitioners of ABMS, as it applies to transportation, are slowly expanding. Numerous interviewees described a progression within the modeling community that is leaning toward ABMS, indicating that usage will continue to grow.[23] Part of this growth is spurred by the anticipation of upcoming Intelligent Transportation Systems deployments and other innovative applications that ABMS can facilitate and enhance. However, because current applications and deployments have been limited to this point, the existing impacts of ABMS have also been limited.

In terms of potential, a number of interviewees noted that ABMS will provide more precision and granularity by incorporating the behavior of individual drivers and actors, eventually leading to better calibrated models that more closely mirror real-world conditions. One interviewee noted this level of calibration in ABMS has been met by other disciplines already by stating the following:

> *"All of those calibration problems ... You might need to run it millions of times. People in physics and astronomy, they have done this for many years; transportation just needs to catch up. There are tools; someone just needs to sit down and figure this out."*[24]

Additionally, there are several innovations and applications that ABMS is uniquely capable of addressing. In particular, one interviewee described how ABMS could be used to model the interaction of autonomous and connected vehicles.[25] The software programming of the vehicles could simply be uploaded into the model to determine the decisionmaking and behavior of the agents. Despite potential upfront costs, preemptively modeling and simulating how to optimize deployment of these systems will become a high priority for State and local transportation agencies.

Through the interviews the evaluation team conducted, it was clear DOE has become increasingly interested in ABMS over the last several years. DOE's interest lies in mapping out user choice regarding charging stations and possible route choices. Researchers from DOE see the transportation-modeling discipline evolving quickly with new technology, such as electric vehicles, automated vehicles, and connected vehicles. This will change the transportation environment dramatically, and they believe ABMS has the potential to model future situations that have no real-world comparison. The concern of how to prepare for future situations was described by one DOE researcher who said the following:

[23]Based on interviews conducted with ABMS stakeholders, phone interviews conducted by Greg Bucci, Michael Green, and Chris Calley (evaluation team), 2016–2017.

[24]Transportation researcher, phone interview conducted by Greg Bucci, Michael Green, and Chris Calley (evaluation team), January 2017.

[25]Federal researcher, phone interview conducted by Greg Bucci and Michael Green (evaluation team), September 2016.

> *"Looking forward, we can model our system from 10 to 20 years ago, but moving forward with new things hitting, we don't have enough baseline data available to create user behavioral models necessary for trip distribution or even simulating vehicle use. You can simulate that, but there aren't real-world data to back that up."*[26]

This quote was taken from a broader conversation about a DOE-sponsored workshop regarding the rapid evolution of surface transportation. Researchers from the transportation-modeling field attended and presented, including those funded by the EAR Program.(48) At this workshop, ABMS was discussed within the context of connected and automated vehicles as a solution to model potential problems or issues before they occur in practice.

As ABMS usage increases, EAR Program–funded and non-EAR Program–funded researchers are continuing to explore ABMS methods and techniques as well as their applications. This includes cross-sector collaboration in science and energy disciplines. This implies that, moving forward, ABMS will be used by a range of practitioners, including researchers and modelers, who do not focus exclusively on transportation. However, barriers inherent to the transportation-modeling industry exist, which will slow the progression.

Finding: Practitioners from different backgrounds believe ABMS can improve the efficiency and reliability of traffic-planning models, eventually improving mobility and safety in practice.

Some large engineering firms specialize in developing tools that State and local transportation agencies can utilize to overcome transportation issues. The private sector is interested in practically applying innovative methods in real-world scenarios. Traffic modeling is useful in modern-day congestion management and in simulating how traffic patterns will change after specific capital investments. By utilizing traffic modeling, agencies can predict the impacts of infrastructure projects, and the upfront costs of simulation can lead to substantial savings for agencies and drivers over time. Through implementing unique behavioral traits similar to real-life actors, typically drivers, ABMS has the potential to provide more accurate simulations and therefore generate cost savings and increased efficiencies for agencies. One practitioner who works with traffic modeling in the private sector believes ABMS has the potential, with enough support, to provide new solutions to the current challenges facing the transportation-modeling field. In other words, ABMS has the potential to model situations that previous traffic-modeling tools are unable to address. The private sector interviewee said the following:

> *"My clients are very interested in travel-time reliability. This is not a theoretical improvement; it's a practical one. For example, we identify advantages in managed lanes. [The tool we are developing] measures improved reliability rather than improved travel time, which is a big revolution in practice."*[27]

This engineer noted that agencies are showing a growing interest in the aspect of travel-time reliability. While improved travel rates are usually aggregated and an average decrease in travel time is noted as a benefit, there can still be peak times of extreme congestion. Travel time–reliability improvements and monitoring can provide drivers with information before their trip that will help them make more reliable predictions and better travel decisions.

[26]Federal researcher, phone interview conducted by Greg Bucci, Michael Green, and Chris Calley (evaluation team), January 2017.
[27]Industry researcher, phone interview conducted by Greg Bucci, Michael Green, and Chris Calley (evaluation team), January 2017.

With travel-time reliability in mind, the Integrated Traveler and Driver Behavior project PI has taken the EAR Program–funded work and built upon it to make a tool that, although still a prototype, is usable by State and local transportation agencies. The tool uses a concept known as behavior user equilibrium (BUE).(49) BUE focuses on a convergence of user choice where each agent or traveler will eventually decide on their preferred travel based on three factors: departure time, mode, and route. The convergence of traveler choices occurs at an equilibrium point when all travelers have decided what decision is best for them personally. Figure 2 demonstrates the process of BUE convergence with the results of the three measured criteria.

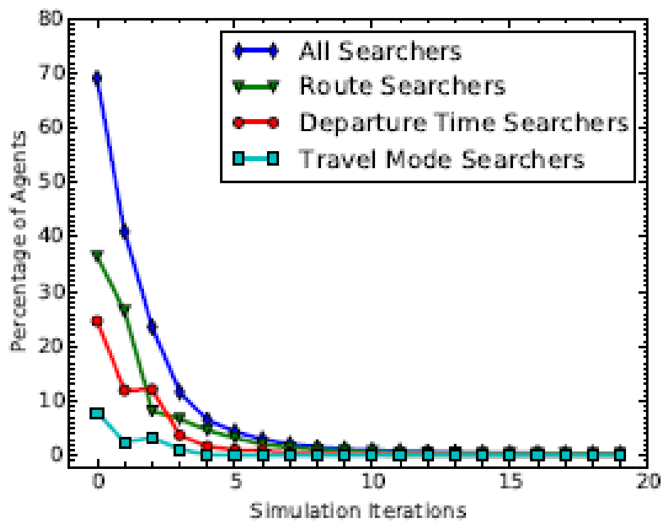




**Figure 2. Graph. BUE convergence and results.(50)**

In figure 2, individual agents are changing their options based on three separate decisions. By the 10th simulation iteration, the agents have converged to an equilibrium and committed to their chosen departure time, mode, and route. This convergence essentially means that travelers have weighed the potential benefits of departure time, mode, and route and then used this knowledge to determine what works best for them personally. Tools like this help State and local transportation agencies better predict how drivers will behave in real-world situations given fluctuating scenarios that involve interacting with other individual agents. With these improved models, agencies will ultimately be equipped to enhance transportation mobility and safety for travelers on their systems.

Finding: ABMS has the capacity to address issues in real time.

ABMS can directly address two common scenarios that cause roadway congestion. The first is traffic-incident management, which is a high priority for State and local transportation agencies. Accidents on State and local roads account for significant costs on a yearly basis in terms of congestion and associated delays. Accidents also create an environment of increased risk for first responders. The application of ABMS in traffic-incident management could lead to reduced risk to first responders and the enhanced ability to adjust to possible congestion. Second, modelers can determine theoretically how individual drivers will react to construction on their preferred routes. This includes learning how severe the delay to drivers will be and what other routes will be affected by the construction activity. This will not only greatly improve mobility and flow but worker safety as well.

ABMS has the potential to aid agencies in addressing traffic-incident management and construction-related congestion by modeling agents or drivers that have simulated traits of real individuals. This allows traffic agencies to more accurately predict the possible outcomes that will occur from actual disruptions. Agencies can then properly prepare contingencies to address these disruptions. This ability has the potential to immediately address these scenarios when they occur. This real-time response capability was noted by an FHWA official who saw the promise of ABMS early on:

> *"Over time, there can be an overall agent-based simulation of a real environment that is running in parallel with reality. If we are able to do that, we now have a model-based version of reality that operators have access to at any time. Now, instead of a planning tool or a project tool, engineers now have a control tool that allows the operator to alleviate congestions or incidents that happen at any certain point."*[28]

ABMS can address transportation mobility, reliability, and safety through real-time response capability. In crafting a parallel simulation to an existing environment, State and local transportation agencies can estimate driver behavior in unique situations that other models have difficulty predicting as quickly. If an agency has a large amount of information that details its traffic environment, it can use these data to simulate what could happen in a future scenario.

[28]Federal researcher, phone interview conducted by Greg Bucci and Michael Green (evaluation team), September 2016.

# 4. Recommendations

The findings highlight the outcomes and impacts of the EAR Program–funded ABMS research activity. While awareness and interest of ABMS is increasing and applications are slowly developing, further development and adoption is yet to occur on a significant scale based on industry factors, such as limited technical expertise and technological capabilities.

Based on these findings and input from interviewees and research conducted, the evaluation team developed a set of specific recommendations for FHWA and the EAR Program. The purpose of the recommendations is to highlight and emphasize specific best practices the EAR Program can undertake to continue the effective development and adoption of exploratory research within the field of transportation.

Recommendation: Establish clear guidelines for project publications, research output, and accessibility to improve program awareness.

One challenge encountered during the evaluation was obtaining access to the final products that resulted from the EAR Program–funded studies. While the Driver Behavior in Traffic report is available on the NTL, it is not currently available on the FHWA EAR Program website. Similarly, the Integrated Driver and Traveler Behavior report is not currently publicly available. Only the VASTO report and the interim Primer report are available for download on the FHWA EAR Program website. References to the projects exist in other article databases, such as TRID, but those sources lack any direct links to the final reports themselves. For example, TRID lists the VASTO project but only includes links to the FS and Primer report. An immediate remedy to this problem is the potential development of an online database that compiles all EAR Program–funded studies. This database could include links to work that has benefited from EAR Program–related efforts.

Aside from their limited availability and access, there are inconsistencies in report formats. The EAR Program–funded work was published by different entities (the funded institutions), and because of this, the report numbers and whether the EAR Program is referenced vary from report to report. In these cases, it is not initially clear that these reports were sponsored by the EAR Program, thereby limiting the awareness of the program overall. Systematically developing FHWA-published technical summaries or final FSs with links to other research output would address these problems and also clearly establish the utility of the EAR Program among researchers.

Another evaluation-related challenge that arose from the issue of report access was the inability to track the contribution of each report through website statistics. The level of statistical analysis that can be done on each website is limited. Some of the Web log reports failed to capture certain website visits and downloads if the total visits or downloads did not meet a certain minimum. Alternatively, free programs exist, such as Google Analytics™, that offer easy-to-use customizable tools to track website access and usage. Data such as international location, age range, and if a user is new or returning can be easier to log over extended periods of time through the use of a tracking code that is inserted into a Web page's code.

Any tool that is used for website statistics remains limited by the pages and reports that are posted on a domain. Only reports that are located on the EAR Program's website can be tracked. By establishing clear ownership of the final product or otherwise producing a technical summary or final

FS, the research can have a greater impact in its respective and related research disciplines. This would also ensure the output is clearly labeled and made readily available through FHWA resources.

Tangentially, for the EAR Program ABMS publications that are available on the EAR Program website, analyzing website statistics became a challenge because each publication can be accessed through multiple links or website addresses. In some cases, varying links would lead to the same page when clicked.[1] In other cases, the complete publication is not available in HTML format. To view the report, users have to either download the PDF or click on links to each individual section of the paper. In addition to making it more difficult for a user to access EAR Program publications, having multiple links limits how well website statistics for an EAR Program product can be tracked overall. To address this, it is recommended that all publications, e.g., reports, summaries, and FSs, are accessible under multiple formats. One link should be available for an HTML format of the document and one link for a PDF when applicable, while eliminating any duplicate links.

Recommendation: Establish a framework for outreach that maintains and supports postresearch-development efforts.

After completion of the three EAR Program–funded studies, efforts were made to discuss the three studies and related ABMS opportunities with the project PIs and FHWA project leaders. While a followup symposium was planned, there was no clear framework for who should lead this effort and who could serve as a secondary lead. Without this framework, and then with subsequent changes in personnel, it was difficult to maintain the momentum needed, and the symposium was indefinitely postponed.

Followup articles and presentations were conducted by the EAR Program–funded PIs; however, the citations for the specific EAR Program–funded final reports are minimal, and the reports themselves have not gained much traction. Establishing a framework or procedure for outreach will ensure that others are made aware of the specific EAR Program–funded work. This will promote the research conducted as well as the EAR Program.

The role of the EAR Program has not traditionally been to continue oversight of the application of research following the completion of a project; however, the program has established a framework for transition support that focuses on communication. The VASTO and Integrated Driver and Traveler Behavior received average marks within this framework and were not selected to receive additional support compared to other EAR-funded projects that scored better. The EAR Program transition-support framework measures projects in terms of timing, potential impact, departmental interest, external interest, and availability of champions. The timing for the ABMS projects was uncertain, the impact and USDOT interest were considered medium, the external interest was high, and champions were available at the time of the assessment (March 2015). Despite this, some postproject activity occurred, including the TRL assessments.

Everett Rogers's seminal 1962 work, *Diffusion of Innovations*, established the need for a champion to make early adopters aware of new technologies.[(51)] Since the EAR Program's focus is to develop such disruptive technologies, the idea of a champion should be built into ensuring these technologies fully develop to the market-ready level. For example, ABMS had such champions, and the conversation surrounding the topic thrived with them as the focal point for bringing the

[1]This issue was primarily due to Web pages that ended with the publication number followed by "/index.cfm" and websites with the "/index.cfm" removed, both resulting in the same Web page. The number of hits varied for each type of ending, and it is not clear if unique or duplicate visitors are accessing these links.

community together. These champions were also significant spokespeople that provided outreach and publicized the EAR Program–funded research.

Most recently, with the departure of such key staff members, practitioners closely following ABMS research have noted a decline in interest and participation. Despite efforts by the EAR Program to find new staff to carry ABMS forward, new champions have not emerged within DOT. To overcome this, a team member, whose responsibilities would be to engage stakeholders and maintain a database of them that can easily be passed along to a successor, could be formally assigned to an EAR Program–funded project. Similarly, at the USDOT level, EAR Program–funded projects could be more formally integrated into offices so that when program office staff changes, support for the project moving forward remains.

Along with existing technology transition-support efforts, the EAR Program and other FHWA R&T efforts should devote more resources to examining what disciplines the research was pursued or implemented in and study how specific concepts that were successful can be applied to other areas. Once a given technology is considered successful, agencies could hold demonstrations to show other transportation professionals how to apply the technology themselves. This would also benefit the EAR Program, as it would further highlight the efforts made in funding exploratory research. In terms of impacts, this would assist in bringing new technologies to smaller agencies that do not have the resources to test theoretical applications themselves.

Further establishing and delineating postresearch efforts beyond the existing publication and transition-support processes will be beneficial both for the EAR Program and for EAR Program–funded researchers. This will be particularly true for projects that are not selected for federally supported, market-ready transition efforts but are still of interest, such as ABMS.

### Recommendation: Establish a framework for considering postresearch development and applications during project screening.

When seeking out potential grant proposals, the EAR Program's grant-making process could include that a small portion of the project be dedicated to describing or delineating possibilities for the transition of early-stage research into continued applied research or possibly real-world uses or applications. By encouraging research to be applied or tested upon completion, and considering those applications initially, more realistic and applicable projects will be proposed. This would further build upon EAR Program efforts to motivate applicants to propose practical innovations with short-term deployment potential. While some highly theoretical research may provide value, it may run the risk of not being further developed if it is unusable in today's transportation environment.

The concept of a "turnkey solution" for ABMS was noted by one interviewee who was a TRL panelist.[2] The panelist noted that innovative research concepts, which are the goal of the EAR Program, need to be walked up from basic research to reproducibility. However, many State and local transportation agencies do not have the research capabilities to make theoretical applications practical (see section 3.2). By establishing possible applications and opportunities for further development from the onset, researchers could lay the groundwork for future work and also ease the transition of research toward deployment and application. Including this component in the initial research will help lower barriers as the research moves forward.

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[2]Transportation researcher, phone interview conducted by Greg Bucci, Michael Green, and Chris Calley (evaluation team), January 2017.

Recommendation: When exploring innovative methods or technology, be careful and deliberate regarding nomenclature and definitions.

While collecting data, the evaluation team noted an interesting trend regarding ABMS. As described in section 1.2, the nomenclature used to describe ABMS is not consistent. In nontransportation disciplines, “agent-based modeling” is referred to as ABM. However, within the field of transportation, ABM is commonly referred to as “activity-based modeling.” As a result, some transportation researchers have begun referring to “agent-based modeling” as AgBM. The EAR Program–funded researchers, in consultation with FHWA stakeholders, chose to use ABMS, referring to “agent-based modeling and simulation.” The lack of consistency highlights the innovative nature of the method, as an industry standard is yet to be established.

Differences in terms is a common aspect in the early exploration of new areas and across domains. For the EAR Program, the primary issue is matching related terms across disciplines and domains during the initial stage of investigation.

Clearly identifying and defining key terms is vital, not only to communicate the results of initial research but also for other researchers and industry stakeholders to build and expand upon the research. In many ways, FHWA and the EAR Program set out to establish a new paradigm within transportation modeling. As a result, using terms and nomenclature in accordance with existing industry standards, or establishing new standards, will enhance the research product and also aid in transferability and uptake by other researchers.

# 5. Conclusions

The EAR Program played a significant role in developing interest and awareness of ABMS within the field of transportation. Prior to the EAR Program activities, ABMS was referenced minimally within transportation contexts and was merely theoretical. However, the EAR Program–funded projects demonstrated the viability of ABMS within transportation. As one interviewee pointed out, the EAR Program and FHWA brought agent-based modeling to transportation.[1]

Significantly, EAR Program–funded researchers are working with MPOs and other agencies to further develop and deploy ABMS tools and methods (MAG in Phoenix, AZ, and the Maryland SHA and the BMC in Baltimore, MD). Since the time the EAR Program began funding ABMS-related work, additional FHWA, DOE, academic researchers, and private practitioners have started to develop and incorporate ABMS models and techniques.

However, barriers exist within the transportation-modeling industry that have hindered the wide-scale development and deployment of ABMS. Despite this, and in large part due to the effort of the EAR Program, ABMS is viewed by transportation professionals and planners as the logical next step in modeling. Many believe that great potential exists, including real-time applications relating to traffic-incident management and construction-related congestion.

Based on these findings, the evaluation team developed four recommendations that could facilitate the further adoption of ABMS as well as other EAR Program projects or initiatives. These recommendations consist of establishing clear guidelines for project publications and research output that are consistent across projects, further establishing and delineating transition support for projects, considering postresearch outreach efforts throughout the process, and establishing clear nomenclature and definitions.

Overall, the EAR Program established and advanced the use of ABMS within transportation modeling. The impacts, including possible safety and mobility improvements, are yet to be determined and will become clearer as the development of ABMS continues. The full impacts of the EAR Program–funded work may expand in the future as usage of ABMS grows within the field of transportation.

[1]Transportation researcher, phone interview conducted by Greg Bucci, Michael Green, and Chris Calley (evaluation team), January 2017.

# Appendix A. Followup Publications From EAR Program–Funded Work

A citation analysis was extended to any and all followup work related to each of the EAR-funded projects. Each list of related publications, presentations, or conference proceedings is included along with a table summarizing the number of times each work has been cited as of December 2017. The citation analysis was carried out using Google Scholar™, Web of Science, and Scopus.[9–11]

## A.1 List of Publications and Citation Analysis Related to Driver Behavior in Traffic

### Publications, Presentations, and Conference Proceedings

Mladenovic, M.N. and Abbas, M.M. (2013). *Self-Organizing Control Framework for Driverless Vehicles*, 16th International IEEE Conference on Intelligent Transportation Systems (ITSC 2013), pp. 964–965, Institute of Electrical and Electronics Engineers, Kurhaus, Netherlands.

Abbas, M.M. and Ghanipoor, S. (2013). "Agent-Based Modeling and Simulation of Connected Corridors: Merits Evaluation and Future Steps." *International Journal of Transportation*, *4*, pp. 71–84, Science & Engineering Research Support Society, Sandy Bay, Australia.

Abbas, M.M. and Ghanipoor, S. (2013). "Modeling the Dynamics of Driver's Dilemma Zone Perception Using Agent-Based Modeling Techniques." *International Journal of Transportation*, *4*, pp. 1–14, Science & Engineering Research Support Society, Sandy Bay, Australia.

Mladenovic, M.N. and Abbas, M.M. (2013). *A Paradigm Shift in Traffic Control of Driverless Vehicles: Improving Mobility and Accessibility Within a Framework of Social Justice*, Proceedings of the Conference on Agent-Based Modeling in Transportation Planning and Operations, Virginia Tech, Blacksburg, VA.

Abbas, M.M. and Mladenovic, M.N. (2013). *Agent-Based Control for Adaptive High-Performance Connected Vehicle Streams*, 2013 International Conference on Connected Vehicles and Expo, pp. 947–948, Institute of Electrical and Electronics Engineers, Las Vegas, NV.

Mladenovic, M.N. and Abbas, M.M. (2013). *Socially Sustainable Control Framework for Self-Driving Vehicles*, 2013 International Conference on Connected Vehicles and Expo, pp. 964–965, Institute of Electrical and Electronics Engineers, Las Vegas, NV.

Abbas, M.M. and Chong, L. (2013). *Car-Following Trajectory Modeling With Machine Learning: Showcase for Merits of Artificial Intelligence*, Presented at the Transportation Research Board 92nd Annual Meeting, Transportation Research Board, Washington DC.

Mladenovic, M.N., Abbas, M.M., and McPherson, T. (2014). *Development of Socially Sustainable Traffic-Control Principles for Self-Driving Vehicles: The Ethics of Anthropocentric Design*, 2014 IEEE International Symposium on Ethics in Engineering, Science, and Technology, pp. 1–8, Institute of Electrical and Electronics Engineers, Chicago, IL.

Abbas, M.M. and Wang, Q. (2016). *Comparison of Dilemma Zone Protection System Using Agent-Based and Discrete Event Simulation*, Presented at the Transportation Research Board 95th Annual Meeting, Transportation Research Board, Washington, DC.

Abbas, M.M. (2015). *BADASS Workshop (Area Wide and Distance-wise Agent-Based Signal-Optimization System)*, Professional Development Workshop to VDOT.

Abbas, M.M. and McGhee, C. (2015). *Agent-Based Reservation System in a Connected/Automated Vehicles Environment—Opportunities and Impacts With High-Priority Vehicles*, Presented at the Automated Vehicles Symposium, Ann Arbor, MI.

Abbas, M.M. (2015). *Agent-Based Modeling, Simulation, and Control—Some Applications in Transportation*, Presented at Workshop III: Traffic Control, Institute of Pure and Applied Mathematics, Berkeley, CA.

Abbas, M.M. (2012). *Agent-Based Modeling and Simulation Workshop*. Presented at the Transportation Research Board 91st Annual Meeting, Transportation Research Board, Washington, DC.

Abbas, M.M. (2014). *Agent-Based Modeling and Simulation in a Connected Vehicle Environment*, Presented to the University of Nevada-Reno, Reno, NV.

Abbas, M.M. (2013). *Modeling the Dynamics of Driver's Dilemma Zone Perception Using Machine Learning Methods for Safer Intersection Control*, Presented to State College, PA.

Abbas, M.M. (2012). *Modeling Drivers' Behavior During Safety-Critical Events With Intelligent Agents*, Presented to the École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland.

## Citation Analysis

Table 9 shows the citation analysis results based on the Driver Behavior in Traffic work. Citations for all published works mentioned in table 9 are available in the preceding list.

**Table 9. Driver Behavior in Traffic citation analysis results.**

| Search Terms | Document Type | Google Scholar™ | Web of Science | Scopus |
|---|---|---|---|---|
| Self-Organizing Control Framework for Driverless Vehicles | Publication | 18 | 5 | 7 |
| Agent-Based Modeling and Simulation of Connected Corridors Merits Evaluation and Future Steps | Publication | 0 | 0 | 0 |
| Modeling the Dynamics of Driver's Dilemma Zone Perception Using Agent-Based Modeling Techniques | Publication | 4 | 0 | 0 |
| A Paradigm Shift in Traffic Control of Self-Driving Vehicles: Improving Mobility and Accessibility Within a Framework of Social Justice | Publication | 2 | 0 | 0 |
| Agent-Based Control for Adaptive High-Performance Connected Vehicle Streams | Publication | 5 | 0 | 1 |
| Socially Sustainable Control Framework for Self-Driving Vehicles | Publication | 5 | 0 | 1 |
| Car-Following Trajectory Modeling With Machine Learning: Showcase for Merits of Artificial Intelligence | Publication | 0 | 0 | 0 |
| Development of Socially Sustainable Traffic-Control Principles for Self-Driving Vehicles: The Ethics of Anthropocentric Design | Publication | 8 | 0 | 2 |
| Comparison of Dilemma Zone Protection System Using Agent-Based and Discrete Event Simulation | Publication | 0 | 0 | 0 |
| BADASS Workshop presentation | Presentation | 0 | 0 | 0 |
| Agent-Based Reservation System in a Connected/Automated Vehicles Environment—Opportunities and Impacts With High-Priority Vehicles | Presentation | 0 | 0 | 0 |
| Agent-Based Modeling, Simulation, and Control—Some Applications in Transportation | Presentation | 0 | 0 | 0 |
| Agent-Based Modeling and Simulation Workshop | Presentation | 0 | 0 | 0 |
| Agent-Based Modeling and Simulation in a Connected Vehicle Environment | Presentation | 0 | 0 | 0 |
| Modeling the Dynamics of Driver’s Dilemma Zone Perception Using Machine Learning Methods for Safer Intersection Control | Presentation | 14 | 0 | 0 |
| Modeling Drivers Behavior During Safety-Critical Events With Intelligent Agents | Presentation | 0 | 0 | 0 |

# A.2 List of Publications and Citation Analysis Related to VASTO

## Publications, Presentations, and Conference Proceedings

Kim, S., Son, Y.J., Tian, Y., Chiu, Y.C., and Yang, C.D. (2017). "Cognition-Based Hierarchical en Route Planning for Multi-Agent Traffic Simulation." *Expert Systems With Applications*, *85*(1), pp. 335–347, Elsevier, Amsterdam, Netherlands.

Kim, S. and Son, Y.J. (2017). "Lane Selection Behavior Modeling in an Agent-Based Traffic Simulation." *Industrial Engineering & Management Systems*, *16*(2), pp. 240–252, Korean Institute of Industrial Engineers, Seoul, South Korea.

Kim, S., Son, Y.J., Chiu, Y.C., Jeffers, M.A.B., and Yang, C.D. (2016). "Impact of Road Environment on Drivers' Behaviors in Dilemma Zone: Application of Agent-Based Simulation." *Accident Analysis & Prevention*, *96*, pp. 329–340, Elsevier, Amsterdam, Netherlands.

Kim, S., Son, Y., Tian, Y., and Chiu, Y. (2014). *Drivers' en Route Divergence Behavior Modeling Using Extended Belief-Desire-Intention (E-BDI) Framework*, Presented at the Winter Simulation Conference, Savannah, GA.

Kim, S., Xi, H., Tian, Y., Son, Y., Chiu, Y., and Yang, C.Y.D. (2014). *Hierarchical en Route Planning Under Extended Belief-Desire-Intention (E-BDI) Framework*, Presented at the Industrial and System Engineering Research Conference, Nashville, TN.

Kim, S., Mungle, S., and Son, Y. (2013). *An Agent-Based Simulation Approach for Dual Toll Pricing of Hazardous Material Transportation*, Presented at the Winter Simulation Conference, Washington, DC.

Xi, H., Kim, S., Feng, Y., Son, Y., Head, L., Zheng, H., Chiu, Y., and Yang, D. (2013). *Drivers' Behavior Modeling and Analysis in Dilemma Zone*, Presented at the Conference on Agent-Based Modeling in Transportation Planning and Operations, Blacksburg, VA.

Kim, S., Xi, H., Mungle, S., and Son, Y. (2012). *Modeling Human Interactions With Learning Under the Extended Belief-Desire-Intention Framework*, Presented at the Industrial and System Engineering Research Conference, Orlando, FL.

Feng, Y., Xi, H., Kim, S., Son, Y., and Head, L. (2012). *A Hierarchical Agent-Based Simulation for Transportation Planning*, Presented at the Council of Engineering Systems Universities, Delft, Netherlands.

## Citation Analysis

Table 10 shows the citation analysis results from sources related to the VASTO work. Citations for all published works mentioned in table 10 are available in the preceding list.

**Table 10. VASTO citation analysis results.**

| Search Terms | Document Type | Google Scholar™ | Web of Science | Scopus |
|---|---|---|---|---|
| Cognition-Based Hierarchical en Route Planning for Multi-Agent Traffic Simulation | Publication | 0 | 0 | 0 |
| Lane Selection Behavior Modeling in an Agent-Based Traffic Simulation | Publication | 0 | 0 | 0 |
| Impact of Road Environment on Drivers' Behaviors in Dilemma Zone: Application of Agent-Based Simulation | Publication | 3 | 1 | 2 |
| Drivers' en route Divergence Behavior Modeling Using Extended Belief-Desire-Intention (E-BDI) Framework | Conference Proceedings | 4 | 3 | 2 |
| Hierarchical en Route Planning Under Extended Belief-Desire-Intention (E-BDI) Framework | Conference Proceedings | 1 | Not indexed | 1 |
| An Agent-Based Simulation Approach for Dual Toll Pricing of Hazardous Material Transportation | Conference Proceedings | 7 | 2 | 6 |
| Drivers' Behavior Modeling and Analysis in Dilemma Zone | Conference Proceedings | Not indexed | Not indexed | Not indexed |
| Modeling Human Interactions With Learning Under the Extended Belief-Desire-Intention Framework | Conference Proceedings | 4 | Not indexed | 3 |
| A Hierarchical Agent-Based Simulation for Transportation Planning, Council of Engineering Systems Universities | Conference Proceedings | Not indexed | Not indexed | Not indexed |

# A.3 List of Publications and Citation Analysis Related to Integrated Driver and Traveler Behavior

### Publications, Presentations, and Conference Proceedings

Zhang, L., Chang, L., Zhu, S., Xiong, C., Du, L., Mollanejad, M., Hopper, N., and Mahapatra, S. (2013). "Integrating an Agent-Based Travel Behavior Model With Large-Scale Microscopic Traffic Simulation for Corridor-Level and Sub-Area Transportation Operations and Planning Applications." *Journal of Urban Planning and Development*, *139*(2), pp. 94–103, The Society, New York City, NY.

Xiong, C. and Zhang, L. (2013). "Positive Model of Departure Time Choice Under Road Pricing and Uncertainty." *Transportation Research Record, 2345*, pp. 117–125, Transportation Research Board, Washington, DC.

Xiong, C. and Zhang, L. (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, Institute of Electrical and Electronics Engineers, Piscataway, NJ.

Chen, X., Zhang, L., He, X., Xiong, C., and Li, Z. (2013). "Surrogate-Based Optimization of Expensive-to-Evaluate Objective for Optimal Highway Toll Charging in Transportation Network." *Computer-Aided Civil and Infrastructure Engineering*, *29*, pp. 359–381, Wiley, Hoboken, NJ.

Xiong, C., Hetrakul, P., and Zhang, L. (2014). "On Ride-Sharing: A Departure Time Choice Analysis With Latent Carpooling Preference." *Journal of Transportation Engineering*, *140*(8), American Society of Civil Engineers, Reston, VA.

Xiong, C., Zhu, Z., He, X., Chen, X., Zhu, S., Mahapatra, S., Chang, G.L., and Zhang, L. (2015). "Developing a 24-Hour Large-Scale Microscopic Traffic Simulation Model for the Before-and-After Study of a New Tolled Freeway in the Washington DC-Baltimore Region." *Journal of Transportation Engineering*, *141*(6), American Society of Civil Engineers, Reston, VA.

Xiong, C., Chen, X., He, X., Guo, W., and Zhang, L. (2015). "The Analysis of Dynamic Travel Mode Choice: A Heterogeneous Hidden Markov Approach." *Transportation*, *42*(6), pp. 985–1002, Springer, New York City, NY.

Zhu, Z., Xiong, C., Chen, X., He, X., and Zhang, L. (2015). "An Agent-Based Microsimulation Approach for the Design and Evaluation of Flexible Work Schedule Policy." *Transportation Research Record*, *2537*, pp. 167–176, Transportation Research Board, Washington, DC.

Xiong, C. and Zhang, L. (2016). "Dynamic Travel Mode Searching and Switching Analysis Considering Hidden Model Preference and Behavioral Decision Processes." *Transportation, 43*(1), pp. 1–18, Springer, New York City, NY.

Zhang, L. and Xiong, C. (2016). "A Novel Agent-Based Modelng Framework for Travel Time Reliability Analysis." *Transportmetrica B: Transport Dynamics*, *5*(1), pp. 78–95, Taylor & Francis, London, UK.

Xiong, C., Chen, X., He, X., Lin, X., and Zhang, L. (2016). “Agent-Based en Route Diversion Simulation: Dynamic Behavioral Responses and Network Performance Represented by Macroscopic Fundamental Diagram.” *Transportation Research Part C*, *64*, pp. 148–163, Elsevier, Amsterdam, Netherlands.

Xiong C. and Zhang, L. (In press). “AgBM-DTALite: An Integrated Modeling System of Agent-Based Travel Behavior and Transportation Network Dynamics.” *Travel Behavior and Society, 12*, pp. 141–150, Elsevier, Amsterdam, Netherlands.

## Citation Analysis

Table 11 shows the citation analysis results from work related to the Integrated Driver and Traveler Behavior work. Citations for all published works mentioned in table 11 are available in the preceding list.

**Table 11. Integrated Driver and Traveler Behavior citation analysis results.**

| Search Terms | Document Type | Google Scholar™ | Web of Science | Scopus |
|---|---|---|---|---|
| Integrating an Agent-Based Travel Behavior Model With Large-Scale Microscopic Traffic Simulation for Corridor-Level and Sub-Area Transportation Operations and Planning Applications | Publication | 21 | 0 | 0 |
| Positive Model of Departure Time Choice Under Road Pricing and Uncertainty | Publication | 14 | 6 | 7 |
| A Descriptive Bayesian Approach to Modeling and Calibrating Drivers' en Route Diversion Behavior | Publication | 11 | 7 | 6 |
| Surrogate-Based Optimization of Expensive-to-Evaluate Objective for Optimal Highway Toll Charging in Transportation Network | Publication | 33 | 0 | 0 |
| On Ride-Sharing: A Departure Time Choice Analysis With Latent Carpooling Preference | Publication | 5 | 1 | 2 |
| Developing a 24-Hour Large-Scale Microscopic Traffic Simulation Model for the Before-and-After Study of a New Tolled Freeway in the Washington DC-Baltimore Region | Publication | 13 | 4 | 9 |
| The Analysis of Dynamic Travel Mode Choice: A Heterogeneous Hidden Markov Approach | Publication | 9 | 3 | 5 |
| An Agent-Based Microsimulation Approach for the Design and Evaluation of Flexible Work Schedule Policy | Publication | 0 | 0 | 0 |
| Dynamic Travel Mode Searching and Switching Analysis Considering Hidden Model Preference and Behavioral Decision Processes | Publication | 8 | 0 | 0 |
| A Novel Agent-Based Modelling Framework for Travel Time Reliability Analysis | Publication | 1 | 0 | 0 |
| Agent-Based en Route Diversion Simulation: Dynamic Behavioral Responses and Network Performance Represented by Macroscopic Fundamental Diagram | Publication | 13 | 0 | 3 |
| AgBM-DTALite: An Integrated Modeling System of Agent-Based Travel Behavior and Transportation Network Dynamics | Publication | 1 | 0 | 0 |

# Appendix B. Technology Readiness Assessments

The EAR Program focuses on higher-risk, higher-reward research that fills the gap between basic research and applied research or development. It also supports the development of transformative research tools that can accelerate the process of developing solutions for highway-related challenges. In fulfilling these missions, the EAR Program identified a need for a system for describing the maturity of highway research products. Such a system would allow experts and nonexperts to (1) document and communicate the maturity of the research at a specific point in time, (2) determine how it might relate to other research, and (3) determine what steps might advance the maturity of a given research product. In a separate effort from this evaluation, the USDOT's Volpe Center adapted the TRL scale for transportation research with these capabilities in mind.(22)

TRLs are formal metrics that support assessments of the maturity of a particular technology and provide the ability to consistently compare levels of maturity between different types of technologies. The TRL scale is a set of questions designed to measure the progress of a technology toward maturity. The concept of TRLs was originally developed by the National Aeronautics and Space Administration (NASA) and later adapted by other Federal agencies, notably the Department of Defense and FHWA/USDOT.

The TRL scale assesses the maturity of a technology in terms of certain characteristics, as measured by successful tests. The scale considers the following aspects of the completed tests:

- How complete was the technology when it was tested? Was it a paper-and-pen concept, a system of equations, a component, a subsystem, or the complete system?
- How representative was the test environment? Was it a computer simulation, a controlled laboratory experiment, a demonstration at a proving ground, or a real-world test? How similar was the tester to the ultimate technology user? Was the tester the developer of the technology, another expert in the field, or a user with no more specific knowledge than the typical technology user?

By focusing on completed tests and a typical progression of testing toward technology adoption, TRLs can be useful for indicating immediate next steps for a research- or technology-development project. The discussion involved in assigning a TRL to a project (in the course of a TRL assessment) can uncover technical gaps and questions that point toward next steps in the technology's development.

The full TRL scale and a description and requirements for each level is presented in table 12.(52)

**Table 12. TRL scale.**

| TRL | TRL Scale | Description | Requirements |
|---|---|---|---|
| Basic research | 1 | Basic principles and research | Do basic scientific principles support the concept?<br>Has the technology-development methodology or approach been developed? |
| Basic research | 2 | Application formulated | Are potential system applications identified?<br>Are system components and the user interface at least partly described?<br>Do preliminary analyses or experiments confirm that the application might meet the user need? |
| Basic research | 3 | Proof of concept | Are system performance metrics established?<br>Is system feasibility fully established?<br>Do experiments or modeling and simulation validate performance predictions of system capability?<br>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?<br>Does a plausible draft integration plan exist, and is component compatibility demonstrated?<br>Were individual components successfully tested in a *laboratory environment* (a fully controlled test environment where a limited number of critical functions are tested)? |
| Applied research | 5 | Integrated components demonstrated in laboratory environment | Are external and internal system interfaces documented?<br>Are target and minimum operational requirements developed?<br>Is component integration demonstrated in a laboratory environment (i.e., 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)?<br>Was the prototype tested in a realistic environment outside the laboratory (i.e., *relevant environment*)?<br>Does the prototype satisfy all operational requirements when confronted with realistic problems? |
| Development | 7 | Prototype demonstrated in operational environment | Are available components representative of production components?<br>Is the fully integrated prototype demonstrated in an *operational environment* (i.e., real-world conditions, including the user community)?<br>Are all interfaces tested individually under stressed and anomalous conditions? |
| Development | 8 | Technology proven in operational environment | Are all system components form, fit, and function compatible with each other and with the operational environment?<br>Is the technology proven in an operational environment (i.e., meet target performance measures)?<br>Was a rigorous test and evaluation process completed successfully?<br>Does the technology meet its stated purpose and functionality as designed? |

| TRL | TRL Scale | Description | Requirements |
|---|---|---|---|
| Implementation | 9 | Technology refined and adopted | Is the technology deployed in its intended operational environment?<br>Is information about the technology disseminated to the user community?<br>Is the technology adopted by the user community? |

While specifically adapted for highway research and the EAR Program, this scale is common within the research community. A NASA researcher first developed a concept for technology readiness in 1974, and it has been adapted to suit other Government agencies' needs ever since. The distance between TRL 1 and TRL 9 often amounts to years of paper studies, prototype modeling, component building and testing, integration of tested components into other systems, and more tests in the laboratory and the real world.(53)

As noted in section 1.2, the three EAR Program–funded projects related to ABMS varied in terms of the TRL scale. Driver Behavior in Traffic was rated as a 2, VASTO was rated between 4 and 6, and Integrated Traveler and Driver Behavior was rated as a 3.

# Acknowledgments

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