Federal Highway Administration

The Potential of Multiple Connected and Federated Simulators and Models for Highway Transportation Research

EXPLORATORY ADVANCED RESEARCH

U.S. Department
of Transportation

**Federal Highway
Administration**

Notice

This document is disseminated under the sponsorship of the U.S. Department of Transportation in the interest of information exchange. The U.S. Government assumes no liability for the use of the information contained in this document.

The U.S. Government does not endorse products or manufacturers. Trademarks or manufacturers' names appear in this report only because they are considered essential to the objective of the document.

Quality Assurance Statement

The Federal Highway Administration (FHWA) provides high-quality information to serve Government, industry, and the public in a manner that promotes public understanding. Standards and policies are used to ensure and maximize the quality, objectivity, utility, and integrity of its information. FHWA periodically reviews quality issues and adjusts its programs and processes to ensure continuous quality improvement.

Technical Report Documentation Page

1. Report No. FHWA-HRT-16-075	2. Government Accession No.	3. Recipient's Catalog No.		
4. Title and Subtitle The Potential of Multiple Connected and Federated Simulators and Models for Highway Transportation Research		5. Report Date December 2017		
		6. Performing Organization Code:		
7. Author(s) Donald Fisher, Nate Deshmukh Towery, Melissa Wong, Elizabeth Machek, Gina Melnik, and Maura Lohrenz		8. Performing Organization Report No.		
9. Performing Organization Name and Address U.S. Department of Transportation John A. Volpe National Transportation Systems Center 55 Broadway Cambridge, MA 02142		10. Work Unit No.		
		11. Contract or Grant No. Contract DTFH61-14-V-00025		
12. Sponsoring Agency Name and Address Federal Highway Administration Office of Corporate Research, Technology, and Innovation Management 6300 Georgetown Pike McLean, Virginia 22101-2296		13. Type of Report and Period Covered Final Report January 3, 2016–July 5, 2016		
		14. Sponsoring Agency Code		
15. Supplementary Notes The Contracting Officer's Representative was Terry Halkyard (HRTM-30), and the Technical Contact was David Kuehn (HRTM-30).				

16. Abstract

Understanding the choices that drivers, bicyclists, and pedestrians make is critical to improving the safety and efficiency of the Nation's roadways. The Federal Highway Administration (FHWA) seeks to understand the technological challenges of advancing the use of federated simulation and modeling and the different uses that researchers and practitioners envision for this technology. This report examines the current state of the practice in connected simulators and related models and the challenges that remain. FHWA also looked at the potential uses for this technology—connecting simulators with simulators, simulators with models, or models with models—and the types of transportation research to which it can potentially be applied to advance research in the areas of safety, operations, planning, and policy. This could lead to decreases in crashes, congestion, and carbon emissions.

An important research tool has been the use of driving simulators to observe and record traveler behavior under a variety of simulated situations. There have been rapid developments in the simulators and related models used that could be applied to highway transportation research. These developments have the potential to advance research in the areas of safety, operations, planning, and policy, which could lead to decreases in crashes, congestion, and carbon emissions. This report addresses these limitations and documents the developments in the simulators that would be beneficial to many in the highway transportation industry.

17. Key Words Simulators, simulation models, driving simulators, modeling, connected driving simulators, driver choices, human factors, safety, operations, advanced research		18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161. http://www.ntis.gov		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified		21. No. of Pages 43	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
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)				
°C	Celsius	1.8C+32	Fahrenheit	°F
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)

Table of Contents

List of Figures

List of Tables

LIST OF ABBREVIATIONS

3D	three-dimensional
ADS	automated driving suite
CAD	computer-aided design
DHS	Department of Homeland Security
DIS	distributed interactive simulation
EAR	Exploratory Advanced Research
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
HERS	Highway Economics Systems Requirements
HLA	high-level architecture
IEEE	Institute of Electrical and Electronics Engineers
ITS	intelligent transportation system
IUPUI	Indiana University–Purdue University Indianapolis
LTAP	left turn across path
MPO	metropolitan planning organization
NADS	National Advanced Driving Simulator
OST-R	Office of the Secretary of Transportation, Office of the Assistant Secretary of Research
OSU	Ohio State University
SHRP2	Second Strategic Highway Research Program
TFHRC	Turner-Fairbank Highway Research Center
TRB	Transportation Research Board
UAS	unmanned aircraft system
V2V	vehicle-to-vehicle
VPN	virtual private network
VRML	Virtual Reality Markup Language

Chapter 1. Introduction

About the Exploratory Advanced Research (EAR) Program

The Federal Highway Administration (FHWA) EAR Program focuses on longer-term, higher-risk research with a high payoff potential. The program addresses underlying gaps faced by applied highway research programs, anticipates emerging issues with national implications, and reflects broad transportation industry goals and objectives.

Motivation

Understanding the choices that drivers, bicyclists, and pedestrians make is critical to improving the safety and efficiency of the Nation's roadways. An important research tool has been the use of driving simulators to observe and record traveler behavior under a variety of simulated situations. However, simulator research has several limitations, particularly in regard to modeling interactions between road users.

In recent years, there have been rapid developments in the simulators and related models that could be applied to highway transportation research. These developments have the potential to advance research in the areas of safety, operations, planning, and policy and could ultimately lead to decreases in crashes, congestion, and carbon emissions. However, there are great challenges as well, according to Jalali et al. as follows:

> Simulation models are typically developed by domain experts who have an in-depth understanding of the phenomena being modeled and are designed to be executed and evaluated independently. A grand challenge is to facilitate the process of pulling all of [the] independently created models together into an integrated simulation environment wherein we can model and execute complex scenarios involving multiple simulators.[1]

FHWA seeks to understand the technological challenges of advancing the use of federated simulation and modeling and the different uses that researchers and practitioners envision for this technology. As such, this report examines the current state of the practice in connected simulators and related models and the challenges that remain. This report also reviews the potential uses for this technology—connecting simulators with simulators, simulators with models, or models with models—and the types of transportation research to which it can potentially be applied.

Defining Connected and Federated Simulators

Connected or federated simulators integrate two or more simulators to better understand transportation systems in a dynamic modeling and simulation environment. For the purposes of this report, simulators may be broadly categorized into driving, pedestrian, bicycle, truck, and bus simulators on the one hand and microscopic and mesoscopic traffic simulators on the other. Transportation planning models could also be connected and are of interest to FHWA.

Each simulator or model in a connected network is called a "federate." The following four major features define the types of connected simulators and models:

- They can all be connected at the same site or distant sites (local or distant).

- They can operate asynchronously (at different times) or synchronously (at the same time).

- They can all be simulating or modeling the same mode of transportation (uni-modal) or more than one mode (cross-modal).

- They can all use the same make of simulator or model (single-platform) or different makes (cross-platform).

This report focuses on the distinction and technical challenges and opportunities of asynchronous versus synchronous federated simulation and modeling at distant sites within a single mode. However, this focus does not indicate a limited interest in just these combinations of features. Table 1 summarizes the types of simulation discussed in this report.

Table 1. Current and future uses of connected simulators and models.

Use	Driving Simulators	Traffic Simulators	Transportation and Planning Models
Current examples	• Effect of cooperative driving behavior during lane change in a multidriver simulation environment. • Effects of advanced driver assistance systems on individual and group levels using multidriver simulation. • Interactions of drivers and bicyclists. • Level of driver emotion in driver-vehicle systems using multiple networked driving simulators.	• Project evaluation. • Corridor evaluation. • Impact assessment of highway projects.	• Long-range planning. • Regional air quality analysis. • Impact assessment of major projects.
Potential applications	• Evaluation of intelligent transportation system (ITS) vehicle-to-vehicle (V2V) solutions. • Passenger vehicle and truck interactions. • Automated vehicles and traditional vehicles. • Vehicle to bike or vehicle to pedestrian.	• Regional traffic modeling on a microscopic scale. • Automated integration of microscopic simulations through travel demand models. • Route choice.	• Evacuation modeling. • Traffic, economic, and land use impacts of differing levels of automated or connected vehicle adoption rates. • Route choice.
Challenges	• Interoperability of simulators at different sites. • Resources to support multiple simulators at one site. • Network latency.	• Automated connections between nanoscopic, microscopic, mesoscopic, and macroscopic simulations.	• Interoperability and standardization.

Chapter 2. Methodology

This report draws on the following three sets of inputs: (1) a detailed review of literature on connected simulators and models, (2) discussions at a workshop on distributed driving simulation held in January 2016 at the Transportation Research Board (TRB) Annual Meeting in Washington, DC, and (3) interviews with selected officials at FHWA whose offices use simulation and modeling in their research programs. The following sections detail each of these inputs.

Literature Review

The research team identified journal articles, technical reports, theses, and other information and placed them into six categories: (1) multiple simulations in transportation, (2) virtual environments, (3) implementation and validation, (4) federated simulation, (5) semantic approaches, and (6) interoperability and model integration. The research team included additional articles if they referenced the original articles or if they were referenced in this report.

TRB Workshop on Distributed Driving Simulation

A workshop titled "Cross-Modal Distributed Simulation" (specifically driving simulation) took place on January 10, 2016 at the TRB Annual Meeting in Washington, DC (see appendix A), co-chaired by Maura Lohrenz (Division Chief, Aviation Human Factors, Volpe) and Donald Fisher (Principal Technical Advisor, Surface Transportation Human Factors, Volpe). Panelists included some of the world's leading experts on distributed asynchronous, distributed synchronous, and cross-modal and cross-platform driving simulation (see appendix B). Workshop attendees represented a broad range of Federal and State agencies, private companies, and universities (see appendix B).

The typical highway transportation research study using driving simulators involves one lab operating one simulator, designing its own scenarios, and testing potential solutions to single-mode problems from one agent's viewpoint (e.g., driver, pedestrian, or bicyclist). This workshop was focused on two related questions. First, what use cases would motivate expansions in highway research simulation infrastructure beyond the standalone, single-mode, and single-platform functionality to encompass distributed asynchronous, distributed synchronous, cross-modal, and cross-platform functionality? Second, what are the technical issues that stand in the way of that expansion? The technical issues for the driving simulation community are mostly specific to the community of researchers at universities, whose resources are often strained both in terms of the technical personnel required to operate complex driving simulators and the funds required to purchase, operate, and maintain them.

The workshop participants generated numerous use cases and identified several technical issues that remain to be resolved before connected driving simulators in all of their various forms are widely available. Use cases were not generated with any particular transportation agency or mission in mind. Rather, they were meant simply to illustrate areas of research where advances in simulation would be

needed to answer critical basic and applied research questions in highway transportation research. An in-depth discussion of the use cases and technical issues is included in appendix A.

FHWA Interviews

The research team conducted interviews in April 2016 with FHWA staff from the Office of Safety; Office of Operations; Office of Planning, Environment, and Realty; and Office of Transportation Policy Studies. Interviewees discussed how simulation in general is currently used in their area, how they are using connected simulators (if at all), and what new problems might be solved with the use of connected simulators. The general finding was that many new problems could be solved in safety, operations, planning, and policy at all levels if more was known about connected simulators, connected models, and connected simulators and models.

Chapter 3. Connected Simulators and Models—Current and Future Uses

This chapter discusses the current and future applications of connected driving and traffic simulators and transportation policy and planning models, as well as technical and resource challenges that may need to be addressed to advance the progress of these federations.

Driving Simulators

Driving simulators are used throughout academia, Government, and the automotive industry to address fundamental and applied research questions. There is a range of floor-mounted driving simulators available, with some having no motion, some having minimal motion, and some being able to simulate almost all aspects of motion. An entirely new category of simulator has recently emerged, which includes both hand-held and head-mounted simulators.

The U.S. Department of Transportation's Office of Safety uses the following three simulators at the Turner-Fairbank Highway Research Center (TFHRC): (1) an advanced driving simulator, (2) a lower fidelity simulator, and (3) a sign simulator. A total of 95 percent of the research funded by the human factors group at TFHRC makes some use of the driving simulators. Examples of research questions addressed on the high-fidelity driving simulator include the following: What happens to drivers approaching an intersection who are caught in a dilemma zone? Does the eye glance behavior of drivers viewing variable message signs, traffic information signs (displaying travel time), or electronic billboards indicate a distraction created by any one or more of these display types? How do different ways of displaying information on active traffic management signs (variable speed signs and lane closure signs) affect drivers' comprehension? An example of a research question addressed on the low-fidelity simulator included an investigation of how well left-turn warning systems functioned when V2V communications were possible.

Connected Driving Simulators

Connecting driving simulators would enable new research. With current driving simulators, it is possible to study the interaction of a driver with another scripted vehicle. However, researchers do not know well enough how drivers interact with one another and other road users. Thus, almost any situation where safety is at issue in an incident involving two interacting drivers requires connected driving simulators communicating with each other in real time. This allows the two or more drivers, bicyclists, or pedestrians to see the same world and the other drivers in that world. Examples of problems that could be studied include the following:

- Combined passenger vehicle and truck simulators could be used to study driver error in car-truck crashes.

- ITSs present drivers with many decisions that are made in real time with other drivers of vehicles. There is no reason to believe that the decisions of drivers when studied alone will reflect the decisions that multiple drivers on the road might make.

- Introducing connected vehicles, which use dedicated short-range communications equipment to enable V2V, vehicle-to-infrastructure, and vehicle-to-pedestrian communication, creates new research questions. A system of drivers may behave very differently than the individual driver alone on the road when they react to potential threats (as indicated by the V2V warning systems) that neither they nor the other drivers can see at the time they are signaled.

- Research is also needed regarding how drivers of traditional and partially automated vehicles will interact with each other, with fully automated vehicles, and with nonmotorized traffic.

- Advanced traffic management could be studied. For example, drivers may be faced with lane closures and need to merge into the next lane. How would this affect the flow of traffic in the next lane? A better understanding of how multiple drivers will respond in a given scenario to the communications from the infrastructure, other vehicles, and other road users is essential to successful adoption of these technologies.

Technical Advances and Challenges

Many of the technical challenges at the most basic level have been overcome for distributed asynchronous simulation at different sites and distributed synchronous simulation at the same site. However, there have been relatively few studies using either of these types of connected simulators. Because the engineering advances required have been available for well over a decade, why has the use of connected simulators for research been so limited? One explanation, discussed at the TRB workshop, is a lack of both available resources and compelling use cases. The next sections discuss asynchronous and synchronous federation at different sites, technical implementation issues, and what advances in technology could reduce these issues.

Distributed Asynchronous Simulation

Distributed asynchronous simulation at different sites has long been possible with driving simulators that provide a medium level of flexibility in programming scenes and scenarios.[2] However, with more powerful simulators, that success has been harder to achieve even though not everything needs to be shared for distributed asynchronous simulation to work. It is enough that two sites have identical visual databases, terrains, scenarios (behaviors), logical road networks, and entity positions. In theory, it should be easy enough to create a model with these shared elements and then run one and the same virtual world (model) on two simulators of the same make at different locations and different times. However, this has turned out to be surprisingly difficult. Software is constantly being updated, and version compatibility issues arise; some simulators use one screen, some three, and some five, creating differences that lead to unexpected problems; and differences exist in the movable objects (e.g., vehicles and pedestrians) across sites that make a motorcycle appear in one simulator and a truck in another for example. All these issues can and have been resolved for limited cases. However, the virtual world built on one simulator cannot simply be copied to another simulator made by the same company and expected to run. Improved interoperability would clearly alleviate many of these problems.

Advances in hardware are helping increase opportunities to connect floor-mounted driving simulators asynchronously and lowering cost while keeping functionality. High-performance mounted simulators that once cost hundreds of thousands of dollars can now cost tens of thousands of dollars.

Finally, cross-platform driving simulation—or crosses between single-purpose, high-fidelity simulators and virtual reality—may be the holy grail of advances in driving simulation, although it is very challenging. To solve this problem, at the very minimum, one needs to ensure that the two platforms render the same world with the same objects. Assuming this can be achieved, there are four options: (1) make both simulators high-level architecture (HLA) compliant and run a common run-time infrastructure, (2) make both simulators distributed interactive simulation (DIS) compliant and pass the scene state back and forth, (3) use the same scenario software in both platforms, or (4) develop a custom interoperability solution.

Distributed Synchronous Simulation
The first study using distributed synchronous driving simulation at a single site was reported in 2003.[3] Very few studies have been reported since, although that number is growing.[1] However, most universities (or other sites where driving simulators are operational) cannot currently afford multiple simulators. Thus, distributed simulation with the current cost structure is typically only going to occur at geographically distant sites. In fact, no studies have been reported at different sites of distributed asynchronous simulation. Currently, across different sites, attempts are being made to implement distributed simulation as a peer-to-peer model. Here, the peers have their own simulation software and compute the state information locally based on the inputs and then pass information through a server about the state (e.g., the position of the vehicles in the local environment), and the server distributes that state information to the other peers. The peers then populate the updated world with the positions of each of the other vehicles and the driver's vehicle. The following three problems unique to distributed synchronous simulation using the peer-to-peer model dominated the workshop discussion: (1) network latency can be too long (greater than 50 ms), (2) network drops can and do occur, and (3) security can be an issue.

There are examples outside of the transportation research community where this geographically distant, synchronous driving simulation occurs. For example, in the gaming industry, long latencies (upward of 500 ms) and network drops are typically dealt with by predicting the behavior of an agent. However, in an experiment designed to uncover the behavior of a driver, this fix is clearly contraindicated. Thus, it is by no means clear that the gaming industry has a solution for the fundamental behavioral problems that face researchers interested in distributed synchronous simulation at distant sites.

Faster internet speeds (lags less than 50 ms) would have a strong impact on researchers' ability to connect driving simulators in real time with one another at different sites. These developments are on the horizon for both copper wire and optic fiber.[4,5]

Perhaps the most disruptive technologies to affect the development of connected simulators across different sites running in real time are head-mounted devices. These devices allow the participant to navigate through an immersive three-dimensional (3D) world (e.g., using virtual or augmented reality), making it possible for the participant not only to navigate through the 3D world but to also see his or her hands on the steering wheel and reaching for the controls, all while receiving feedback.[6] Connecting tens, hundreds, or thousands of drivers in the same virtual world simultaneously may soon be

---

[1]Thomas Kerwin, personal communication of Donald Fisher with Thomas Kerwin, Ohio State University (OSU), January 8, 2016.

technically feasible. For drivers using connected simulators to see another driver's head, eye, and hand movements, there will need to be the development of avatars in the simulated vehicles of the other drivers that will capture said movements. No current examples were found.

Traffic Simulators

Similar to driving simulators, there are also several different types of traffic simulators. These include nanoscopic (individual vehicles and driver behaviors), microscopic (vehicles), mesoscopic (groups of vehicles), and macroscopic (aggregate flows only). Traffic simulators are also classified according to whether they are continuous or discrete in the time, space, and state domains.

FHWA's Office of Operations frequently uses traffic simulation in areas such as congestion management, ITS deployment, traffic operations, emergency management, and freight management and operations. Through the Second Strategic Highway Research Program (SHRP2), the Office of Operations has developed a multiresolution modeling framework that ties together macroscopic models of traffic in distinct transportation subnetworks such as freeways, corridors (including freeways and parallel arterials), surface street grid networks, and rural highways; microscopic models that predict individual vehicle trajectories and diversions, which are especially useful for congested conditions, complex geometric configurations, and system-level impacts of proposed transportation improvements; and mesoscopic models that tie together the macroscopic and microscopic models. The traffic analysis tools are now being supplemented with those needed for integrated corridor management (the reduction of underused capacity in the form of parallel roadways, single-occupant vehicles, and transit services that could be better leveraged to improve person throughput and reduce congestion) and active traffic demand management (the dynamic management of recurrent and non-recurrent congestion based on prevailing and predicted traffic conditions).

Distributed Asynchronous Simulation and Modeling

Distributed asynchronous traffic simulation has been available for some time; FHWA pioneered the development of guidelines over a decade ago.[7] Unlike the software for driving simulators, the software for traffic simulators is not typically configured for a particular site. Moreover, there are generally no connections to hardware that further complicate the possibility of distributed, asynchronous traffic simulation. Therefore, researchers can and do replicate each other's simulations at different sites.

A promising direction in distributed traffic simulation is the development of nanoscopic and microscopic models that can be used to influence operations, planning, and policy at much larger scales than previously possible.[8] By connecting or federating traffic simulators, much larger regions could be modeled at a microscopic level. There is also a real need for connecting different categories of simulators and models. For example, through the SHRP2 C10A project, researchers have developed an integrated traffic modeling framework with true interoperability. It starts with an activity-based travel demand model. The outputs (origin-destination tables and activity matrices) of the travel demand model are then fed into a mesoscopic model to get traffic flows and capacity constraints, which are then input into a microsimulation model to evaluate the effects of a strategy (e.g., ramp metering) in terms of impact on traffic flows. The outputs of the microsimulation model are then fed back into the mesoscopic model to get new diversions that will also affect demand (e.g., time of departure or mode choice), which are then fed back to the activity-based travel demand model to get new demands until one reaches convergence. Each time a transition between levels (simulation or models) is made (from macro- to meso- to micro- and back), the fidelities are different and critical information is lost. Improvements in

the interoperability of different categories of connected simulators and models would improve the situation considerably.

Distributed Synchronous Simulation and Modeling

Distributed synchronous simulation has also been around for over a decade.[9] Its use makes it possible to employ multiple microscopic simulators in the analysis of a transportation network in real time as opposed to the analysis of a single location. The computational load is distributed across perhaps hundreds of different computers. This can be done in several ways. This report focuses only on spatial distribution or decomposition; the traffic network is decomposed into separate traffic sub-networks, and communication is needed only when one vehicle must travel to an adjacent subnetwork.[9] A distributed database must be maintained to hold the results, and a distributed synchronization mechanism is used to coordinate the flow of information.[10] While there are challenges, they are generally less difficult than those that occur in the world of driving simulation, where latency on the order of milliseconds affects performance. With distributed traffic simulators solving problems in real time, the level of analysis may be as large as a second or longer.

Another future direction might combine driving and traffic simulators, something that has already been done with a single driving and traffic simulator.[11] However, as previously noted, with the advances in technology, there will soon be an opportunity to bring together tens of thousands of participants making route choices while driving simulators in real time. Those choices would be embedded within a distributed nanoscopic traffic simulators that update their models based on the driver choices.

Technical Advances and Challenges

There are several technologies that have enabled the technical advances in connected traffic simulation. Perhaps of most general importance are increased computer capabilities (central processing unit speed and random access memory) and advances in the tools and techniques used to distribute the computational load across multiple processors and computers. Also important is the development of methods to maintain interoperability across distributed simulations. In fact, many articles in the literature review address issues of interoperability of distributed simulations. The majority of this research (i.e., 9 out of 10 articles) was published after 2010. (See references 12–20.) Finally, within the traffic simulation community, there has been a large advance in the efficiency of various algorithms central to performance. Given the previous discussion, there is much to be done in improving existing technologies.

Connected Transportation Planning Models

Travel demand modeling and prediction is a complex process that requires input from more general models of land use and more detailed simulations of traffic.[21] The transportation models and traffic simulators are now connected but only loosely. Land use—where houses will be built and where jobs are located—is something that transportation planners have to consider because it drives transportation needs of individuals. Land use changes happen slowly, with visible changes happening 2–30 years after they are discussed. Therefore, transportation planners start by looking 2–30 years in the future from today's conditions at what the land use models predict will happen.

The traditional four-step approach to travel demand modeling dates back some 50 years, with the following four steps:

- Trip generation—Estimating the numbers of trips that will be made at future trip productions (e.g., home) and attractions (e.g., work).

- Trip distribution—Modeling the origin and destination of those trips.

- Mode choice—Estimating how trips will be divided among the various modes (e.g., single occupant auto, carpool, transit, and nonmotorized)

- Trip assignment—Determining the actual routes on highway or transit networks that will be used for the trips.

Metropolitan planning organizations (MPOs) and State transportation departments use the four-step process for comprehensive multimodal transportation planning, air quality conformity analysis, and major project evaluation.

The four-step process has received some criticism that the steps are not well integrated and that trips do not occur in isolation. In reality, travelers engage in tours with multiple stops, and the mode chosen for the first leg of a tour may affect which modes are available for subsequent legs. For example, if a traveler left his or her car at home and took transit to work, then he or she is unlikely to use that car for a lunch outing.

As computers have become more capable and transportation planning problems have become more complex, several trends have emerged. First, the use of activity-based models has become more common, particularly at large MPOs.[22] An activity-based modeling framework (figure 1) considers household activities and tours, deriving individual trips from the tours.
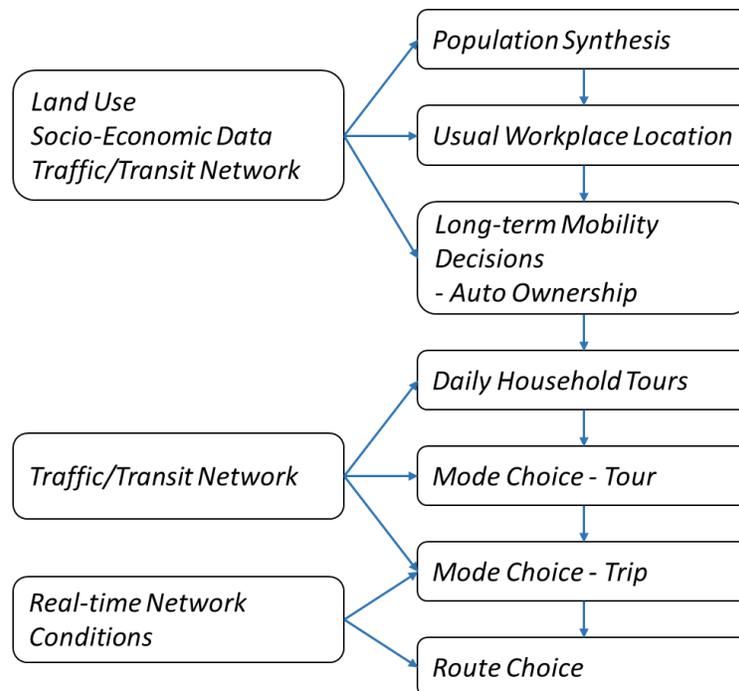
Figure 1. Flowchart. Generic activity-based modeling framework.

Second, dynamic traffic assignment models have emerged for route choice assignment.[23] These models perform the route choice function at a greater level of temporal and spatial detail than older traffic assignment models. In some cases, traffic microsimulation has been used on a regional level.

Third, models have begun to address greater spatial and temporal detail. A traditional four-step process using the computers of several decades ago might have divided an entire metropolitan area into a few thousand zones while considering traffic assignment for four broad periods of the day (morning peak, midday, afternoon peak, and night). More recently, some cities have built models based on individual land parcels, while others have created models with a time-of-day resolution measured in minutes rather than hours. With finer-grained time resolution, it becomes possible to analyze short-lived congestion issues and real-time traffic management strategies.

Fourth, there is an interest in model integration. For example, the Rapid Policy Assessment Tool is one of several strategic planning tools that deal with aspects of both transportation and land use. Several SHRP2 capacity pilots are underway to integrate activity-based models and dynamic traffic assignment.

Connected interoperable models will become increasingly important in the very near future because of what one cannot do in the modern policy environment, especially for planning models, which is to build new policy contingencies into a model. For example, suppose that someone has a regional demand model and is attempting to take into account automated vehicles and how they are deployed (e.g., in fleets, with individual owners, and/or as shared use cars). There are many permutations in the automated vehicle space (e.g., synchronizing signals and how many cars are equipped with automated driving suites (ADSs)). Trying to code all of these permutations into a detailed regional demand model is a next to impossible task. Instead, one could construct simplified planning models (e.g., on the effects of automated vehicles that may be reflected in a traffic model via car following) that can include conceptual findings from other models and adjust accordingly. Simply put, what is required is an educated guess based on the outputs from another model and the ability to integrate that educated guess seamlessly into a heavy-duty traffic model. This level of interoperability would provide not only labor savings but also the flexibility to alter assumptions efficiently and interrogate assumptions and compare them with data from implementation on the roads.

Connected Transportation Policy Models

There are many different types of models used in the formulation of transportation policy. Among the various economic models used, one can undertake the following four types of analyses: cost effectiveness analyses, benefit-cost and net benefit analyses, lifecycle cost analyses, and multiple accounts evaluation. The economic models are used to determine value of a policy, project, or program.

For example, FHWA's Office of Transportation Policy Studies has sponsored the development of the Highway Economics Systems Requirements (HERS), an engineering and economic analysis tool. The tool uses engineering standards to identify highway deficiencies and then applies economic criteria to select the most cost-effective mix of improvements for system-wide implementation. HERS is designed to evaluate the implications of alternative programs and policies on the conditions, performance, and user cost levels associated with highway systems. The model provides cost estimates for achieving economically optimal program structures as well as predicting system condition and user cost levels resulting from a given level of investment. The cost equations are always being updated to reflect new realities. Many other tools are available.

There are several questions that could be answered if the research questions addressed with traffic and driving simulators were formulated in the context of the issues critical to the HERS model and then could easily be input to the HERS model. First, consider traffic simulators. In the HERS model, there are equations that predict the vehicle operating costs per mile traveled. These costs include fuel consumption, tire wear, oil consumption, maintenance and repairs, and mileage-related depreciation. There are also equations that relate those costs to characteristics of a roadway section, which are needed because the HERS model evaluates improvements that would add to highway capacity by adding lanes or improving pavement condition through resurfacing and reconstruction. Both types of improvements will affect operating costs, and traffic simulators could provide the required information. Next, consider driving simulators. Behavioral studies on driving simulators that would be valuable for models like HERS include research, which leads to a better understanding of the impact of system-wide congestion pricing, the discomfort costs of driving on rough pavements on an aging highway system, the influence of curvature on speed, the effect of different levels of automation on the cost of the time spent in a vehicle, the effect of variable speed limits, and the impact of real-time traveler information on drivers' route choices. In terms of safety, most of the things that could be studied with driving simulators would be of some value to the HERS model. For example, if research through connected driving simulators or other means could provide better information about how highway conditions like congestion would affect the rates of crashes of different severities and how the radical improvements in vehicle technologies in the future would affect the crash rates, then all of this information would be useful for the HERS model.

Chapter 4. Conclusion

There are many potential advances in transportation safety, operations, planning, and policy if the simulators and models used had a much higher level of interoperability. For such advances to take place, there needs to be improvement, not only in interoperability, but in the software that is the brains of the simulators and models and in the hardware that is the brawn. This also requires models to communicate across different sites with lags as small as 50 ms. With such advances, one can potentially make progress on the many issues that will arise in the very near future as the highway infrastructure ages. At the same time, advances in vehicle technologies and short-range communications will catapult us into the future where smart cities are just over the horizon. Fully automated vehicles are a much larger part of the vehicle mix, and vehicles, pedestrians, bicyclists, and the infrastructure can talk with one another. The potential of multiple connected, federated simulators and models for highway transportation research is great.

Appendix A. Summary of TRB Workshop

Researchers held a workshop titled "Cross-Modal Distributed Simulation" in Washington, DC, on January 10, 2016, that was co-chaired by Donald Fisher (Principal Technical Advisor, Surface Transportation Human Factors, Volpe) and Maura Lohrenz (Division Chief, Aviation Human Factors, Volpe). The list of attendees is included in table 2 in appendix B.

Purpose

The typical highway transportation research study using driving simulators involves one lab operating one simulator, designing its own scenarios, and testing potential solutions to single-mode problems from one agent's (e.g., driver's, pedestrian's, bicyclist's, etc.) viewpoint.[24] This workshop was focused on two related questions. First, what use cases would provide a motivation for expanding the Nation's highway transportation research simulation capabilities beyond the standalone, single-mode, and single-platform functionality to distributed, cross-modal, and cross-platform functionality? The proposed use cases were not generated with any particular agency or mission in mind. They were meant simply to illustrate areas of research where advances in simulation would be needed to answer critical basic and applied research questions. Second, what are the technical issues that stand in the way of that expansion? The technical issues are mostly specific to the community of researchers at universities, whose resources are often strained both in terms of the technical personnel required to operate complex simulators and by the funds required to purchase, operate, and maintain them.

Background

Central to the discussion of any type of distributed simulation is the importance of being able to replicate what any researcher has demonstrated. Many human factors experiments only require a single computer and monitor. The stimuli that are presented to participants can be easily and fully described in written documentation. However, that is not the case with experiments done on a driving simulator. An investigator who wants to replicate another investigator's experiment must have access to adequate documentation to understand the source or executable code. This is the only way to match the precise detail in the scenes and scenarios, including the exact interaction among the host vehicle, scripted vehicles, ambient vehicles, and signalization. Some simulators with limited capabilities can replicate what was done at one site on a given platform onto another site on the same platform.[2] For simulators with advanced software that give researchers more power in generating scenes (especially complex roadway geometries) and scenarios (especially complex interactions among vehicles, pedestrians, and signals), however, it can often be quite challenging or even impossible to replicate a given model.

There is a critical need for distributed simulation as more and more decisions about what treatments to implement are being made initially on the basis of experiments run on simulators. Specifically, unless other investigators can replicate an experiment, the findings from just one experiment run by one set of investigators may be suspect. This need was originally addressed in a TRB workshop back in 2005.[25] The current workshop is the next logical progression in the advancement of distributed simulation.

Use Cases

The workshop attendees proposed and briefly discussed several possible use cases for four categories of simulation. The major focus of the workshop was not on the detailed exploration of use cases; the focus was on identifying a representative sample of use cases for each of the categories. Various relevant references (which were not explicitly recorded in the workshop minutes) are included in the following subsections to substantiate points made at the workshop. In several cases, this summary elaborates on points that were discussed briefly in the workshop so that they are understandable to the larger audience.

Distributed Asynchronous Simulation Use Cases

There are surprisingly few examples of human-in-the-loop transportation research using the same scenarios on the same platform (brand of simulator) at different locations and different times. Until recently, there were very few simulators of the same brand that had the functionality required to evaluate complex scenarios with novel roadway designs and signals. Thus, there simply was not the capacity to move forward in this arena. In addition, it is difficult to run the same virtual world (model) on the same platform at different locations. The proposed use cases for this category of simulation are described in the following sections.

Different Regions—Geometric Design, Signs, Signals, and Pavement Markings

It is important to analyze the effect of different treatments designed to increase safety with drivers from different regions of the country. In terms of signs, signals, and pavement markings, it simply cannot be known a priori whether red light cameras or dynamic speed feedback signs, for example, will have the same effect in one region of the country as they do in another. Understanding how drivers in different regions will respond to new treatments only becomes possible with distributed asynchronous simulation (and, in fact, may require distributed synchronous simulation).

Different Populations

Increasingly, manufacturers are designing treatments for special populations of drivers who are at a greatly increased risk of crashing, including older drivers—as they become a larger fraction of the total driving population—and teen drivers, especially those with Attention Deficit Hyperactivity Disorder.[26] Studies often need to include hundreds of participants, but the number of participants from a given subpopulation at any one geographic location may be limited. Distributed asynchronous simulation is needed to successfully study the problem using driving simulators.

Distributed Synchronous Simulation Use Cases

Distributed synchronous simulation can be performed at one of the following three levels: (1) micro (2 simulators), (2) mini (3–10 simulators), and (3) macro (up to thousands of simulators).[27] The need for distributed synchronous simulation is driven by the importance of understanding the complex interactions among two or more drivers. A recent motivation for understanding this interaction in more depth is the role of the human operator in the rapid advance of automated vehicles, vehicle-to-object (i.e., other vehicle, pedestrian, bicycle, or infrastructure) communications, and ITSs. These and other possible use cases for distributed, synchronous simulation are discussed in the following subsections.

Crash Avoidance Science

As noted previously, only a handful of referred articles have captured drivers' joint behavior in the seconds leading up to a crash.[3] However, 40 percent of traffic fatalities occur in multiple-vehicle crashes.[28] A better understanding of the joint and codependent behavior of drivers in these multiple-vehicle crashes can lead to better remediation. The following use cases provide examples of where a better understanding is needed.

Roadway Design

To date, researchers have evaluated new roadway designs, such as the diverging diamond interchange using a standalone simulator.[29] However, to gain a deeper understanding of driver behavior while they are operating in these new roadway configurations, researchers need to study multiple road users in the same virtual world at the same time. Comparisons could then be made between the behavior of multiple independent drivers in standard diamond intersections with highway on and off ramps and the behaviors of multiple independent drivers in the diverging diamond interchange.

Head-On Collisions

In some states, high-speed roads (70 mi/h or more) with one travel lane in each direction and with no median to separate the lanes are common. Head-on collisions are often deadly. Understanding how two drivers behave in this scenario could provide the information needed to better train drivers to mitigate such situations. This is a clear case in which how drivers respond to each other in the last few seconds before a crash requires two real drivers operating in the same virtual world. Researchers cannot reliably script the real-life behavior of another human driver in this case, and the only safe way to study this scenario is with driving simulators because the crashes are so deadly.

Left Turn Across Path (LTAP)—Four-Way Intersections

Besides a head-on collision, one of the deadliest crashes for older and younger drivers alike is an LTAP of an oncoming vehicle at a four-way intersection (typically signalized). New V2V communications have the potential to facilitate much earlier warnings delivered to drivers. What the turning driver and through driver typically do in such scenarios during the last several seconds is critical to the design of any LTAP collision warning systems. However, little is known about this. As in the head-on collision, using driving simulators is the only safe way to study this scenario.

Left-Turn—T-Intersections

Equally problematic is a driver turning left at a T-intersection.[30] Intersection mitigation assist warnings based on V2V communications will be useful only to the extent that researchers understand how the drivers receiving these warnings interact with one another.

Car Following in Congested Traffic

Models of a driver following another car are used frequently in microsimulations of high-volume traffic.[31] However, a thorough understanding of the interactions that occur between and among drivers and the consequent effects on congestion is not currently available.

Rear-End Crashes

Off the highway, it can reasonably be argued that many rear-end crashes could be avoided if the struck driver of a stopped or slowing vehicle knew that another vehicle was about to strike his or her vehicle. V2V communications make such warnings possible, but how will the driver of the struck vehicle react?

On the highway, it will be possible, with V2V communications, to know when a lead vehicle (many vehicles ahead) slows suddenly or stops. This information can be propagated V2V upstream of the slowing vehicle, but how the drivers in the convoy will react to the warning and to each other is not known.

Emergency Vehicles

Many emergency vehicles (e.g., firefighters, ambulances, and police) sometimes need to coordinate as a team in response to unexpected, large-scale events. Understanding how they interact with one another and with surrounding non-emergency vehicles could provide improvements in the quality and speed of the response. Some work in this area has been undertaken using simulated environments.

ITSs—Route Choice

Standalone driving simulators have been used to study route choice in which the driver is in an immersive environment.[32] However, this is somewhat unrealistic because many real-time decisions about which route to take are made in congested traffic, which is also responding to travel information. Mini-driving simulations and macro-driving simulations have been used to understand route choice, but in these distributed synchronous experiments, the driver is not in an immersive environment and is simply making decisions without the attendant cognitive and manual load that comes with driving in congestion.[33] Virtual reality technologies make possible the study of route choice in immersive environments across hundreds of drivers who are all interacting with one another.

Smart Signs and Signals

The suburbs are shrinking, and cities are growing and becoming ever more congested. Building new or expanded roadway capacity is not viable in most cases. Instead, transportation planners must focus on making the signs and signals smarter at directing traffic to keep it flowing more smoothly. The algorithms that control the smart signs and signals are often based on rudimentary information about driver-driver interactions. The knowledge gained from distributed asynchronous simulation of driver-driver interactions in a new environment of smart signs and signals could add to the fidelity and, therefore, effectiveness of control algorithms that make assumptions about these interactions.

Automated Vehicles

The workshop attendees were in general agreement that automated vehicles at level 3—in which the ADS is in control for much of the trip—probably will not be on the roads in large numbers in the near future except in dedicated lanes. Knowing how drivers interact with one another in a dedicated lane when following each other at short distances is important, especially when, because of emergencies, control must be transferred to every driver in a convoy. There are more issues for automated vehicles at level 2, where the driver can have both hands and feet off the controls but is supposed to maintain situation awareness. Little is known about how to make sure that the driver maintains situation awareness or how to transfer control to the driver from the ADS. In addition, from the standpoint of distributed synchronous simulation, it is critical that researchers understand how drivers of non-automated vehicles will interact with drivers of level 2 automated vehicles. A driver of a level-2 automated vehicle may not retake control as quickly as possible when his or her vehicle operates outside its designed envelope. How drivers of non-automated vehicles react to such scenarios is unknown.

V2V Communications

LTAP and rear-end crashes are two examples of crash scenarios where it is important to understand how two or more drivers involved in a potential collision would respond to whatever new warnings V2V communications can provide.[34] Certainly, these are not the only crash scenarios where V2V communications will prove helpful. There are both applied and basic questions to which researchers will want to know the answers that can be provided best by understanding driver interactions in distributed synchronous simulations.

Evacuation

Minidriving and microdriving simulations cannot model what happens when an entire city must evacuate. Macrosimulation now makes this possible. A better understanding of how drivers behave in situations where they must evacuate an area may become more critical as abrupt changes in the weather leave less time for evacuation. How drivers respond to one another in such situations will be critical to understanding how any evacuation plan will potentially work in practice.

Cross-Modal Simulation

The use cases for cross-modal simulation will become more important over the next 30 years as society moves closer to the vision of a world without traffic.[35] If today's predictions hold true, growing numbers of pedestrians and bicyclists will coexist with autonomous and semi-autonomous vehicles. Simulators are needed with two or more modes in which operators in these different modes can simultaneously navigate the same virtual world.

Truck–Car Interactions

The determination of fault and unsafe driving acts in truck–car crashes has been difficult at best.[36] The ability to study truck–car crashes in a cross-modal simulator would allow a much more complete evaluation of hypotheses about the determination of the fault and the unsafe driving acts that lead to these crashes.

Emergency Vehicle–Private Vehicle Interactions

The interaction of emergency vehicles with other types of vehicles on the highway is not well understood, in part because there has not been the cross-modal simulation capacity to support the relevant research. If the research were only focused on the interaction of police cars and private cars, the advances could perhaps be made using the capabilities of distributed synchronous simulation. However, a study of cabs with very different interiors and types of operation, such as those of a fire engine and those of a private car, would almost necessarily need to involve two modes.

Vehicle–Pedestrian Interactions

Pedestrian behavior is one of the most difficult behaviors to script. It is impossible to realistically study the interaction that occurs between pedestrians and vehicles (e.g., cars, trucks, and buses) at intersections and marked midblock crosswalks, which are two locations where pedestrians are particularly at risk of being struck by a vehicle.[37,38] Marked midblock crosswalks represent a multiple-threat scenario in which a pedestrian just entering the crosswalk is obscured from the view of drivers approaching the crosswalk in the left of two travel lanes by a vehicle stopped in the right travel lane immediately adjacent to the crosswalk. The question to which researchers have no answer, and which seems absolutely essential to understanding this deadly mix, is what happens when either the driver,

the pedestrian, or both are distracted. Does the distracted driver fail to swerve, or does the distracted pedestrian freeze in place when suddenly one or the other is confronted by the unexpected? Researchers can only understand how drivers and pedestrians respond in these situations by studying and evaluating them in a safe, simulated environment. The goal would be to use the results of such experiments to develop appropriate designs, warnings, and training to mitigate the problem.

Vehicle–Bicycle Interactions

Bicycle fatalities are on the rise, increasing by 19 percent since 2010.[39] Right-hook crashes, in which the striking vehicle is often a truck or bus, are particularly deadly. Following these crashes, investigators seek to answer the following questions: Was the driver of the vehicle not looking? Was the driver looking but the bicyclist not visible? Where was the attention of the bicyclist? Would all right-hook crashes be preventable if the driver were paying attention and scanning appropriately? Would all such crashes be preventable if the bicyclist were paying attention? The answers to these questions, like the answers to the multiple-threat scenario for pedestrians, depend on researchers being able to observe the behaviors of the agents in the last few seconds before a crash occurs.

Interactions Among Drivers in Coordinated Teams of Vehicles

The workshop participants briefly discussed the use of cross-modal simulation to understand the coordination that is required by drivers in a team of vehicles (e.g., emergency responders). This coordination is presumably a major concern of the Department of Homeland Security (DHS). The participants were not certain whether DHS had used cross-modal simulation to evaluate how teams of drivers would coordinate their response to an emergency. However, given that this coordination is essential and multiple modes of transportation are involved, cross-modal simulation would be needed to adequately study this case. What is not clear is whether the simulation needs to be immersive. The participants suggested that interactions among the different modes of emergency responders probably do not require the fine detail that is necessary to understand vehicle–pedestrian and vehicle–bicycle conflicts. Rather, the cross-modal simulation should simply be able to capture decisions being made by the different units, not the actual behaviors of the vehicles operating in the different units.

Interactions Within a Mixed Fleet of Automated, Semi-Automated, and Traditional Vehicles

None of the workshop participants knew of prior research that had studied the behavior of drivers in a mixed-fleet environment in which some vehicles are autonomous, some are semi-autonomous, and some are "traditional" (i.e., not autonomous). In particular, if a driver of a traditional vehicle encounters a driver of an automated vehicle, then researchers need to know how the traditional driver will respond to the driver of the automated vehicle, who may not be attending to the forward roadway. Driving simulation studies cannot fully address this difficult problem until the avatar in the simulated world (representing the driver of the autonomous vehicle) can be realistically programmed to communicate his or her exact intentions (or lack thereof) to the traditional driver in a way that the traditional driver can understand. To understand this communication well enough to develop such a realistic avatar, researchers first need to use cross-modal simulation to study both human agents interacting in real time.

Cross-Platform Simulation

The use cases previously described also motivate the need to advance the state of the art with respect to cross-platform simulation. Specifically, each of these use cases assumes the availability of a second

platform functionally identical to that which initiated the sharing of scenes and scenarios. Usually, however, the second site to which a researcher needs access has a driving simulator with a different platform. Therefore, there is a need for infrastructure that enables the evaluation of virtual worlds across different platforms.

Cross-platform functionality can also enable the evaluation of test scenarios that are initially developed on a less expensive platform (i.e., without full functionality) to be quickly and easily evaluated more fully on a platform with full functionality (e.g., the full-motion National Advanced Driving Simulator (NADS) platform). Without cross-platform support, this process is much more resource intensive because the entire virtual world must be developed twice (once for each platform). This additional cost often means that changes in roadway design that are evaluated initially on a lower-fidelity platform are never evaluated in a high-fidelity simulator. Cross-platform simulation would resolve this issue.

Technical Issues

High-fidelity driving simulators are operationally unique, complex entities. Each consists of a set of hardware and software components, along with application drivers, compilers, and interpreters that facilitate the underlying input/output process. The hardware includes the vehicle controls, visual displays, input/output devices, possible motion platform, cab enclosure, speakers, and other peripheral devices that can assimilate data synchronously via the application program interface. The software that controls what is presented and how it is presented includes the following:

- What is seen, which depends on the underlying logical road network, terrain, entities, (vehicles and people) and image generator.

- What is heard, which depends on the surround sound system.

- How an individual moves through the world and the world responds to the individual, which includes the vehicle dynamics and the scenario and terrain details.

Scene and Scenario Development

One of the first steps in designing a new simulation is to develop the scenes (the static world) and scenarios (dynamic world) through which a driver (or drivers) can navigate. The workshop participants addressed various aspects of this often-painstaking process, including the growing need for project deliverables that require custom virtual worlds, which cannot be developed easily using the tools native to most driving simulators. "Custom virtual worlds" means environments that need to precisely reflect the geometry and visual appearance of the roadway in a given locale and must include novel roadway or intersection designs that have never been built before.

To understand the difficulties that the developer encounters using the current set of tools to accomplish the steps in the previous paragraph, it is necessary to understand how developers generally construct a virtual world with the software native to most driving simulators. Most driving simulators come with an interface that allows for the use of premade tiles, which contain already built sections of roadways, intersections, etc. The roadway sections are either straight (with single-, two-, or four-lane roads) or curved (left, right, and spiral), and there are a limited number of different curves, intersections, roundabouts, etc. The scene is developed by adding objects in the built and natural environment to the

tiles using a set of objects that have been made available in a library. Textures can be applied to the objects and the roadway, but the basic geometry cannot change. If a researcher wants to have complete control over the roadway geometry and at the same time have the geometry conform to highway design guidelines, the researcher needs computer-aided design (CAD) software. Therefore, the person doing the development has to learn complex 3D modeling software. In addition, the researcher needs an application to do the texturing, which need to be applied to all of the many hundreds and perhaps thousands of polygons. This will continue to be the case for the new roadway designs that the researcher is evaluating (the experimental sections of the roadway).

However, what about the transition sections between the new designs that the researcher is evaluating? It is these sections of roadway that sponsors are indicating the need to be very close in appearance to the roadways in a given location or region. Therefore, the researcher still needs the complex set of 3D modeling and texturing tools for the transition sections to get them to appear like the roads in a given location. An alternative, proposed and piloted by Kelvin Santiago at the University of Wisconsin–Madison, has shown to greatly reduce the time it takes to create the transition sections in custom virtual worlds. Using Santiago's tools, researchers can quickly and easily generate roadway surfaces specific to any given locale without resorting to complex

3D modeling of every polygon and subsequent texturing of those polygons. A textured 3D model is output as a file which is in a format that requires conversion to another file before it can be read directly by the software running on NADS. In particular, the format of file containing the textured 3D model is a dot object file (obj file). That file is then converted into a Virtual Reality Markup Language (VRML) file that can be read directly by the NADS' software. Using Santiago's software, researchers can easily define and combine the location of travel lanes with the roadway surface information (which is necessary for autonomous vehicles).

Santiago uses one of two approaches to perform the previously described process with transition sections. First, when a CAD file is available (e.g., from a local transportation department), he uses open-source software (e.g., CAD tools) for extracting a polyline that defines the center of the roadway and any polylines that define other important features (e.g., a bike path or sidewalk). The Python scripts then take the polyline and automatically build a 3D model. Textures are automatically applied to the polygons in the 3D model. Alternatively, when a CAD model is not available, Santiago creates a polyline by tracing a picture of a roadway in a CAD package, creating, for example, one edge line. The pictures of the roadway used for tracing can be obtained from several different external sources. Just as before, he uses this tracing (or polyline) to automatically generate the 3D model that will have a geometry indistinguishable from the transition section in the real world that is being duplicated in the simulator.

Success Stories

Santiago has used this tool to model the transition sections that occurred between a complex interchange in Sioux City, IA. Santiago built the transition sections between the interchange easily using the Python scripts to automatically generate the textured 3D models from the polylines without having to resort to manually constructing all of the polygons or manually applying all of the textures.

Distributed Asynchronous Simulation Technical Issues

Once a virtual world is created, a researcher would like to share it with other investigators using the same platform for all of the reasons previously discussed. Fortunately, not everything needs to be shared for distributed asynchronous simulation to work. It is enough that two sites have identical visual

databases, terrains, scenarios (behaviors), logical road networks, and entity positions. Technically, it seems like it should be easy enough to create a model with these shared elements and then run one and the same virtual world (model) on two simulators of the same make at different locations and different times. However, this has turned out to be surprisingly difficult. The workshop participants mentioned the problems and possible solutions listed in the following sections. It is important to note the difference between what used to be called source code and executable code. Source code can be edited by the user. Executable code cannot be edited by the user. The same distinctions are not as hard and fast in today's simulator software environment, but there are parallels.

Different Versions

While the simulators at two institutions may be the same, the versions of the software can still be (and often are) different. Most of the model may transfer, but not all of them will. For example, suppose a researcher uses the retro-reflectivity feature on traffic signs on a later version of the software at one site. Another site that uses an earlier version cannot support the reflectivity because of the non-availability of the feature on older versions of the software. Problems also come with upward compatibility. It can often take less time to completely reprogram scenarios than it can to make them upwardly compatible. In addition, small changes in the code syntax and semantics also surface on occasion (such as the use of the enumeration function) in advanced versions of the simulation software. Furthermore, the sound module may be set up differently at different sites. For example, at the University of Massachusetts Amherst, the environmental and external roadway sounds are emitted by surround speakers that function off the left channel. However, the scripted audio sounds are played using a second auxiliary model on the center channel. Other universities and research centers may have other setups. (Often, they use a single model to play different sounds.) The software is incredibly complex, so perhaps it is not surprising that upward compatibility is not always achievable.

Different Visual Databases and Different Vehicles

Two institutions may want to work together on the development of the same virtual world (visual database). However, pointers in the source code to objects (e.g., cars, pedestrians, or buildings) on one simulator may not address the same objects on a different simulator. (For example, vehicle number 5 in a simulator may be a bicyclist on one simulator and a truck on another simulator.) This flexibility is necessary given that different installations require different traffic environments and the number of moving objects that can appear simultaneously and are under the control of operator written code during a simulation is rather small (30–50 in many simulators). When the references are not the same across platforms, either different objects or blank white space (indicating a "dead" texture) will appear. Again, these differences arise naturally because different institutions will have different needs (and so their library of objects will be different). However, that creates problems. One way around this is to use only published code. Another reliable way is to share the resource folder associated with that scenario VRML file (the "res" folder contains all of the textures used in that scenario). However, the published model cannot be modified except by adding new objects to it (existing objects cannot generally be changed), which can change the environment in ways that make the altered virtual world different from the original virtual world.

Different Configuration Files

Perhaps slightly more pernicious, if only because they are less obvious to the developer, are the many settings on the multiple configuration files (also referred to as component model files or *.cmp files), including those for vehicle dynamics (e.g., steering, braking, acceleration or gain), visuals (e.g., time of

day or fog), scenarios (e.g., characteristics of how the world is drawn), and terrain (e.g., roadway friction or surface properties). The configuration files have a complex set of features that need to be defined. Field of view is one feature, change in the horizon with braking is another feature, and so on. Differences between two sites may immediately stand out in these cases. However, that is not true of other features. For example, the vehicle dynamics of the host vehicle at two different institutions will likely differ from one another. Steering and brake inputs are just two aspects that might not be the same. This means that the timing in the scenarios can be thrown off at complex intersections. Going through the configuration files for every feature that might be set differently is critical, and there is no simple way to equate all of the configuration files for two sites. Nevertheless, as long as the researcher remembers to check that all of the features on all of the configuration files are set identically, what might appear before the researcher does this as different virtual worlds will appear after all the configuration files have been equated as similar virtual worlds. One potential workaround is where one makes critical vehicle dynamics and scenario-specific changes directly in the JavaScript file specific to the model and then shares this JavaScript for the configuration file (component model file) across sites. (Each configuration file has a unique JavaScript file associated with it.) As a working example, the University of Massachusetts Amherst and the University of Wisconsin–Madison were previously engaged in a two-site study understanding driver behavior at flashing yellow arrows that used this workaround.

Success Stories

There are an increasing number of success stories as different investigators learn which factors determine whether a world at one site will run at another site. For example, among universities with a simulator, the University of Massachusetts Amherst has successfully shared scenarios with the University of Wisconsin at Madison, the University of Pennsylvania, the University of Puerto Rico at Mayaguez, and North Carolina Agricultural and Technical State University. In first attempting to successfully share scenarios, knowledge of the previously listed issues arose (requiring a lot of trial and error).

Distributed Synchronous Simulation Technical Issues

Assuming a researcher can get the same virtual world to appear at two locations asynchronously, there are now significant technical challenges that come with trying to get drivers to navigate through the same virtual world simultaneously while seeing the actions of the other driver(s). Several problems and solutions are mentioned in this section, which considers the problems that occur at one site with multiple simulators and then the problems that occur at sites at different locations, each with one or more simulators.

There are three ways to implement distributed simulation. The first way is labeled "server master." The client has no simulation software; the server has the only simulation software. In this case, driver inputs are passed to a central computer that does all of the calculations and passes the entire virtual world as modified back to the clients. This model can potentially be implemented at a single site with multiple simulators but would require more bandwidth than is currently available across multiple sites.

The second way is labeled "client-server input sharing." The client and the server are both running simulation software. The client provides the server at each update with inputs on steering, braking, and acceleration, and the server computes the new positions of the client vehicles and passes that information back to the client which redraws the position of the vehicles at the next update.

The third way is labeled "client-server state sharing." The clients pass information through a server about the state (the position of the vehicles), and the server distributes that to the other clients. The clients then recompute the positions of each of the other vehicles and the driver's (client's) vehicle at each update. This is the type of distributed asynchronous simulation that is typically used across sites.

One Site and Multiple Simulators

Multiple simulators at the same site may have no networking complications or problems. Two simulators, a desktop sim, and a motion-base sim at the OSU Driving Simulation Laboratory are connected by a single gigabit switch and get sub-millisecond latency for communication. With the distributed nature of simulator software, the multiple simulators are treated similarly to one simulator.

Multiple Sites and One or More Simulators at Each Site

With geographically distant sites, traffic across the Internet is needed, and this requires additional network infrastructure. OSU has a local simulator network along with connections to outside networks. The simulator networks communicate with one another over the Internet using the security provided by a virtual private network (VPN). The OpenVPN server is usually on the host network (in this case OSU). The OpenVPN client is at the remote site. Typically, this is accomplished using OpenVPN software with level-2 bridging.

Network Latency

There are challenges associated with latency. First, the communications usually travel over the commercial Internet. In that case, network latency is not in the researcher's control. Data travels at approximately 120,000 mi/s (120 mi/ms). Therefore, if information traveled in a straight line over the Internet, it would take about 4 ms. Additional latency is introduced by the numerous switches along the path to the destination. The typical measured latency using a digital subscriber line from OSU to the University of Massachusetts Amherst is 33 ms.[2] The latency to Indiana University–Purdue University Indianapolis (IUPUI) is almost identical (29 ms).

What might happen with a lag of, for example, 500 ms, which is larger than one that would necessarily occur in practice for two simulators but is fairly routine in the gaming world? Suppose Driver 1 and Driver 2 started side by side in a race for example. If the lag were 500 ms, then Driver 1 would have traveled half a second before Driver 1 saw Driver 2's vehicle start to move. Similarly, Driver 2 would have traveled half a second before Driver 2 saw Driver 1's vehicle start to move. Each driver's behavior subsequently will be different from what it would be if they understood that they were neck and neck, not each leading the other. Therefore, researchers would lose the control that makes simulator-based experiments invaluable.

One of the solutions to the latency problem is to try and predict the course of user-controlled characters and vehicles. This is common in video game engines where the latencies can be up to 500 ms. However, this type of prediction can be counter to the design of driving simulation experiments where one is interested in operator behavior and subtle, unpredictable actions are most interesting. Thus, predicting what another driver will do robs the experiment of the purpose for which it is intended—to understand the interactions between and among drivers.

---

[2]Personal Interview with USDOT Subject Matter Expert (2016). John A. Volpe National Transportation Systems Center, Cambridge, MA. 16 March 2016.

Network Drops

Second, there are network drops where packets are simply lost. As with long latencies, researchers can do some client-side predictive modeling. However, this way of dealing with what is occurring with another driver when a network drop occurs has problems similar to the issue with network latency when it comes to attempting to evaluate hypotheses about what a driver would do.

Common Model Look Up

Care must be taken to ensure that the running simulated world is shared between users. Randomness added to improve realism in the simulated world must be replicated to all users before being displayed. Having disagreements about distances and object qualities would eliminate most useful data from an experiment. There is also what is referred to as the problem of common model look up. Is a driver at one site really seeing what a driver at another site is seeing? For example, one person sees a red van, but another person sees a blue truck. This problem was referred to in the discussion of distributed asynchronous simulation. This issue can also arise if the moving objects (such as vehicles and actors) are differently mapped across different sites (a definite possibility). Vehicle 1 at University of Massachusetts Amherst may be a red sport utility vehicle while Vehicle 1 at FHWA may be a white truck.

Security

There are also the ubiquitous problems associated with security. Although using a VPN does not eliminate all security issues, the security issues surrounding it are known and relatively uncomplicated. There is no obvious alternative to a VPN at the moment.

Success Stories

OSU has also been successful at getting their simulator network (Center for Automotive Research West) to communicate with the simulator network at IUPUI. OSU is getting its simulator network to communicate with the simulator network at the University of Massachusetts Amherst as well. On a much larger scale, a U.S. company that provides computational simulation and modeling has built a network of 18 simulators with the possibility of more for the University of New South Wales, Australia.

Cross-Modal Simulation

The technical challenges are no different for cross-modal simulation than they are for distributed asynchronous simulation, assuming that the simulators for the different modes can be constructed. Once developers (or "researchers") have constructed those different simulators and assuming that they are being run on the same platform, it is network latency, network drops, and common model look up that are the real challenges.

Success Stories

One of the major cross-modal success stories is the car-bicycle simulator at Oregon State University. Bicyclists and drivers can navigate in the same virtual world and see one another as agents in that world. OSU is now constructing a cross-modal car–pedestrian simulator. The motion base simulator at the OSU Driving Simulation Lab will communicate with a system at the Ohio Supercomputer Center Interface Lab.

Cross-Platform Simulation

Cross-platform simulation may be the holy grail of advances in simulation. Technically, it is very challenging. When the configuration files on the same platform at different sites differ, at least the corrections to those problems involve identical changes. However, when the configuration files differ, as they will across platforms, then exactly how one configuration plays out (e.g., rain) on one platform may be very different than it plays out on another platform. In fact, cars, lights, and other scenario objects may have very different behaviors. Furthermore, there is a lack of a common world and objects in that world. A red sedan should show up as a red sedan for everyone, not as a red sedan for a driver at one site and a blue truck for a driver at another site.

To solve this problem, at the very minimum, a researcher needs to ensure that the two platforms render the same world with the same objects. Assuming that this can be achieved, there are the following four options: (1) make both simulators HLA compliant and run a common run-time infrastructure, (2) make both simulators DIS compliant and pass state back and forth, (3) use the same scenario software in both platforms, or (4) develop a custom interoperability solution.

The HLA standard has enabled some interoperability, as defined under the Institute of Electrical and Electronics Engineers (IEEE) standard 1516.[40] The HLA standard resembles a middleware that runs on top of a run-time infrastructure. HLA provides the following three main advantages: (1) interface specification (i.e., it defines how simulators interact with the run-time architecture), (2) an object model template (i.e., it specifies what information is communicated between simulators), and (3) a set of rules that simulators must obey to be HLA compliant. However, there is no standardization of the network protocol. The different sites must then use common libraries for the application to be able to achieve interoperability.

The DIS standard has also enabled interoperability, as defined under IEEE standard 1278.[41] DIS does not use a central computer to coordinate simulations. In that sense, it supports peer-to-peer interactions. DIS does specify the protocol on the wire, unlike HLA. It communicates with every other simulator and passes information back and forth (not used as a central computer). DIS simulations are responsible for updating the state of their own objects. Each car is responsible for broadcasting its own state. DIS supports dead reckoning, which works similarly to client-side prediction, but it uses a simplified model. Unfortunately, DIS and HLA are not compatible (which is unsurprising because they are very different), and a researcher needs adapter software to cross-communicate.

Options 3 and 4, although possible, are not likely unless an agency decides to fund a project that requires the implementation of either one of the options. However, they may be chosen as an interim milestone on the path toward fully complying with one of the standards. Finally, it should be noted that HLA and DIS don't solve problems such as common model lookup.

Success Stories
There are success stories such as massively multiplayer online games, real-time strategy games, and the synthetic theater of war, just to name a few. However, current success stories in driving simulation are nonexistent.

Human-in-the-Loop Simulation in Aviation

As with surface transportation, there are many primary agents in a simulation. These include pilots (for both planes and unmanned aircraft systems (UASs)) and air traffic controllers (including en route, terminal, tower, oceanic, and international) along with a bevy of other individuals who are involved in airline operations, dispatching, mission control, traffic flow management, and airport operations, among others. Use cases revolve around the issues faced by these agents: new technologies, new procedures, new airspace and airport designs, new aircraft types and capabilities, proposed future traffic volumes and mixes, extreme weather conditions, and congestion and delays. The simulators needed to evaluate the different use cases are multiple, including a NextGen Integration and Evaluation Capability simulator, a Cockpit Simulation Facility, an air traffic control tower (Research Development and Human Factors Laboratory), a UAS Human-in-the-Loop Laboratory, and an Airway Facilities Tower Integration Laboratory.

For distributed simulation, the Federal Aviation Administration (FAA) interacts with companies and agencies who use both DIS and HLA. DIS is the IEEE standard architecture created for Department of Defense war gaming. It was widely adopted sometime before the mid-1990s. While it is relatively simple and lightweight, it is not as capable as modern architectures. Nevertheless, it is still useful for simulation interoperability but only within a local area network. If an external group has a DIS-compliant simulator and can bring it to FAA, FAA can connect to it. With respect to HLA, FAA typically uses the civilian version known as AviationSimNet®. This allows real-time human-in-the-loop simulation at geographically disperse locations to study complex Air Traffic Management scenarios. It has been widely adopted by aviation research facilities in industry, academia, and the Government.

Appendix B. TRB Workshop Attendees

Table 2. Workshop attendees.

Role	First Name	Last Name	Organization	City	State	Country
P	Kenneth	Allendoerfer	FAA	Atlantic City	NJ	United States
P	Donald	Fisher	OST-R/Volpe Center	Cambridge	MA	United States
P	Thomas	Kerwin	OSU	Columbus	OH	United States
P	Maura	Lohrenz	OST-R/Volpe Center	Cambridge	MA	United States
P	Michael	Manser	Texas A&M Transportation Institute	Austin	TX	United States
P	Kelvin	Santiago	University of Wisconsin-Madison	Madison	WI	United States
P	Chris	Schwarz	University of Iowa	Iowa City	IA	United States
P	Heather	Stoner	Realtime Technologies, Inc.	Royal Oak	MI	United States
A	Sehyun	Tak	Korea Advanced Institute Science and Technology	Daejeon	N/A	South Korea
A	Fedesa Itefa	Geleta	WBI Worldwide Engineering	Weinheim (Bergstrae)	N/A	Germany
A	Jeroen	Hogema	TNO	Soesterberg	N/A	Netherlands
A	Aquilino	Alvarez-Castro	ACCIONA Infraestructuras S. A.	Alcobendas	N/A	Spain
A	Richard	Romano	University of Leeds	Leeds	N/A	United Kingdom
A	Mohamed	Ahmad	University of Wyoming	Laramie	WY	United States
A	Omar	Ahmad	University of Iowa	Iowa City	IA	United States
A	Jasmine	Amanin	Virginia Department of Transportation	Charlottesville	VA	United States
A	Jonathan	Fok	University of Wisconsin	Madison	WI	United States
A	James	Jenness	WESTAT, Inc.	Rockville	MD	United States
A	Gina	Melnik	OST-R/Volpe Center	Cambridge	MA	United States
A	Edward	Otani	Mazda North American Operations	Irvine	CA	United States
A	George	Park	Systems Technology, Inc.	Hawthorne	CA	United States
A	Siby	Samuel	University of Massachusetts, Amherst	Amherst	MA	United States
A	Andrew	Veit	NADS	Iowa City	IA	United States

Note: P = Presenter; A = Attendee; N/A = Not applicable.

References

1. Jalali, L., Talcott, C., Venkatasubramanian, N., and Mehrotra, S. (2012). "Formal Specification of Multisimulations Using Maude." Proceedings of the 2012 Symposium on Theory of Modeling and Simulation—DEVS Integrative M&S Symposium, pp. 22:1–22:8, Society for Computer Simulation International, San Diego, CA.

2. Allen, R., Park, G., Cook, M., and Fiorentino, D. (2007). "The Effect of Driving Simulator Fidelity on Training Effectiveness." DSC 2007 North America, University of Iowa, Iowa City, IA. Available online: https://www.nads-sc.uiowa.edu/dscna/2007/papers/Section%206A%20-%20Training/Allen.pdf, last accessed January 31, 2016.

3. Hancock, P. and de Ridder, S. (2003). "Behavioural Accident Avoidance Science: Understanding." *Ergonomics, 46*, pp. 1111–1115.

4. Bautista, C. (2014). "New Internet Speed Record is 10 Times Faster Than Google Fiber." Tech Times. Available online: http://www.techtimes.com/articles/10156/20140711/draft-new-internet-speed-record-10-times-faster-than-google-fiber.htm, last accessed February 27, 2016.

5. Huang, H. et al. (2015). "Mode Division Multiplexing Using an Orbital Angular Momentum Mode Sorter and MIMO-DSP Over a Graded-Index Few-Mode Optical Fibre." *Nature: Scientific Reports, 5*, pp. 14931.

6. Gallee, G. (2015). "VR/AR & Transportation—Examples from Industry, Road Safety and Simulation Conference." Orlando, FL. Available online: http://safersim.nads-sc.uiowa.edu/uploads/article_30/RSSS%202015%20-%20Workshop%20VR-AR%20-%20Gilles%20GALLEE%20-%20OPTIS.PDF, last accessed February 27, 2016.

7. Dowling, R., Skabardonis, A., and Vassili, V. (2004). *Traffic Analysis Toolbox Volume III: Guidlines for Applying Traffic Microsimulation Modeling Software*, Report No. FHWA-HRT-04-040, Federal Highway Administration, Washington, DC.

8. Xu, J. and Lin, Y. (2014). *A Networked Multi-Drivers Simulation Platform for Interactive Driving Behavior Study*, Driving Simulation Conference, Paris, France.

9. Potuzak, T. (2007). *Distributed Traffic Simulation: State of the Art and Future Research*, University of West Bohemia, Plezn, Czech Republic.

10. Ai, W., Xinsong, L., and Kejian, L. (2006). *A Pure Distributed Framework for Large-Scale Microscopic Traffic Simulation*, Seventh International Conference on Computer-Aided Industrial Design and Conceptual Design, Hangzhou, China.

11. Hou, Y., Zhao, Y., Hulme, K., Huang, S., Yang, Y., Sadek, A., and Qiao, C. (2014). "An Integrated Traffic-Driving Simulation Framework: Design, Implementation, and Validation." *Transportation Research C, 45*, pp. 138–153.

12. Camus, B., Christine, B., and Chevrier, V. (2015). *Combining DEVS with Multi-Agent Concepts to Design and Simulate Multi-models of Complex Systems*, Centre National de la Research Scientifique, Paris, France.

13. Dascalu, S., Fritzinger, E., Okamoto, S., and Harris, F. (2011). "Towards a Software Framework for Model Interoperability." IEEE International Conference on Industrial Informatics, pp. 705–710, Institute of Electrical and Electronics Engineers, Lisbon, Portugal.

14. Diallo, S., Tolk, A., Graff, J., and Barraco, A. (2011). "Using the Levels of Conceptual Interoperability Model and Model-Based Data Engineering to Develop a Modular Interoperability Framework." Proceedings of the 2011 Winter Simulation Conference, pp. 2571–2581, Winter Simulation Conference, Pheonix AZ.

15. Jalali, L., Mehrotra, S., and Venkatasubramanian, N. (2014). "Simulation Integration: Using Multidatabase Systems Concepts." *Simulation, 90*, pp. 1268–1289.

16. Pierzchala, D. (2014). "Application of Ontology and Rough Set Theory to Information Sharing in Multi-Resolution Combat M&S." *Advanced Approachess to Intelligent Information and Database Systems*, pp. 193–203, Springer International Publishing, Cham, Switzerland.

17. Siegfried, R., Luthi, J., Rother, M., and Hahn, M. (2013). *Limiting Issues for True Simulation Interoperability: A Survey Done by MSG-086 and Resulting Recommendations*, Spring Simulation Interoperability Workshop, pp. 211–221, Simulation Interoperability Standards Organization, San Diego, CA

18. Walsh, E., O'Connor, A., and Wade, V. (2013). "The FUSE Domain-Aware Approach to User Model Interoperabilty: A Comparative Study." Proceedings of the 2013 IEEE 14th International Conference on Information Reuse and Integration, pp. 554–561, IEEE Computer Society, San Francisco, CA.

19. Xu, X. and Li, G. (2013). *A Management and Control Infrastructure for Integrated Real-Time Simulation Environment*, 2013 IEEE/ACM 17th International Symposium on Distributed Simulation and Real Time Applications (DS-RT), IEEE/ACM, Delft, The Netherlands.

20. Zhou, Q., Prasanna, V., Chang, H., and Wang, Y. (2009). *A Semantic Framework for Integrated Modeling and Simulation of Transportation Systems*, 12th IFAC Symposium on Control in Transportation Systems, Redondo Beach, CA.

21. Transportation Research Board. (2007). *Metropolitan Travel Forecasting: Current Practice and Future Direction*, Special Report 288, Transportation Research Board, Washington, DC.

22. Transportation Research Board. (2014). Activity-Based Travel Demand Models: A Primer, Transportation Research Board, Washington, DC. Obtained from: http://onlinepubs.trb.org/onlinepubs/shrp2/SHRP2_S2-C46-RR-1.pdf, last accessed September 23, 2016.

23. Transportation Research Board. (2011). *Dynamic Traffic Assignment: A Primer*, Transportation Research Board, Washington, DC. Available online: http://onlinepubs.trb.org/onlinepubs /circulars/ec153.pdf, last accessed September 23, 2016.

24. Fisher, D., Rizzo, M., Caird, J., and Lee, J. (Eds.). (2011). *Handbook of Driving Simulation for Engineering, Medicine and Psychology*, CRC Press, Boca Raton, FL.

25. Fisher, D.L., Mourant, R., and Rizzo, M. (2005). *Development of Standardized Descriptions of Driving Simulator Scenarios: Human Factors Considerations*, Committee on Simulation and Measurement of Vehicle and Operator Performance and the International Simulator Users Group, Washington, DC.

26. Insurance Institute for Highway Safety. (2013). "Fatality Facts 2012: Older People." (web page) Insurance Institute for Highway Safety, Arlington, VA. Available online: http://www.iihs.org/iihs/topics/t/older-drivers/fatalityfacts/older-people, last accessed January 21, 2016.

27. National Highway Traffic Safety Administration. (2009). *Traffic Safety Facts: 2008 Data*, National Highway Traffic Safety Administration, Washington, DC. Available online: http://www-nrd.nhtsa.dot.gov/Pubs/811162.PDF, last accessed January 26, 2016.

28. Muhlbacher, D., Zimmer, J., Fischer, F., and Kruger, H.-P. (2011). "The Multidriver Simulator—A New Concept of Driving Simulation for the Analysis of Interactions Between Several Drivers." *Human Centered Automation*, pp. 147–258, Shaker Publisher, Maastricht, The Netherlands.

29. Federal Highway Administration. (2007). *Drivers' Evaluation of the Diverging Diamond Interchange*, Report No. FHWA-HRT-07-048, Federal Highway Administration, Washington, DC. Available online: http://www.fhwa.dot.gov/publications/research/safety/07048/07048.pdf, last accessed January 31, 2016.

30. Katsikopoulos, K., Duse-Anthony, Y., Fisher, D., and Duffy, S. (2000). "The Framing of Drivers' Route Choices When Travel Time Information is Provided Under Varying Degrees of Cognitive Load," *Human Factors, 42*, pp. 470–481.

31. Yasar, A., Berbers, Y., and Preuveneers, D. (2008). *A Computational Analysis of Driving Variations on Distributed Multiuser Driving Simulators*, IASTED International Conference on Modeling and Simulatoin, Quebec City, Quebec, Canada.

32. Cai, H., Lin, Y., and Cheng, B. (2010). "Mimicking Human Driver Behavior for Realistic Simulation of Traffic Flow." *International Journal of Simulation and Process Modeling, 6*, pp. 126–136.

33. Bonsall, P. (2004). "Route Choice Simulators." *Human Behaviour and Traffic Networks*, pp. 167–191, Springer-Verlag Berlin Heidelberg, New York, NY.

34. Department of Transportation. (2015). *Beyond Traffic: 2045: Trends and Choices*, Department of Transportation, Washington, DC. Available online: https://www.transportation.gov/sites/dot.gov/files/docs/Draft_Beyond_Traffic_Framework.pdf, last accessed January 28, 2016.

35. Sawyer, B. and Hancock, P. (2012). "Development of a Linked Simulation Network to Evaluate Intelligent Transportation System Vehicle to Vehicle Solutions." Proceedings of the Human Factors and Ergonomics Society Annual Meeting, pp. 2316–2320, SAGE, Boston, MA.

36. Federal Highway Administration. (2007). *Highway Safety Information System: An Examination of Fault, Unsafe Driving Acts, and Total Harm in Car-Truck Collisions*, Report No. FHWA-HRT-04-085,

Federal Highway Administration, Washington, DC. Available online: http://www.fhwa
.dot.gov/publications/research/safety/humanfac/04085, last accessed January 31, 2016.

37. National Highway Traffic Safety Administration. (2015). "Bicyclists and Other Cyclists." *Traffic Safety Facts: 2013 Data*, National Highway Traffic Safety Administration, Washington, DC. Available online: http://www-nrd.nhtsa.dot.gov/Pubs/812151.pdf, last accessed January 31, 2016.

38. Dommes, A., Cavallo, V., Dubuisson, J., Tournier, I., and Vienne, F. (2014). "Crossing a Two Way Street: Comparison of Young and Old Pedestrians." *Journal of Safety Research, 50*, pp. 27–34.

39. Gomez, R., Samuel, S., Gerardino, R., Romoser, M., Collura, J., Knodler, M., and Fisher, D. (2011). "Do Advance Yield Markings Increase Safe Driver Behaviors at Unsignalized, Marked Midblock Crosswalks: A Driving Simulator Study." *Transporation Research Record, 2264*, pp. 27–33, Transportation Research Board, Washington, DC.

40. Institute of Electrical and Electronics Engineers. (2010). *IEEE Standard for Modeling and Simulation (M&S) High Level Architecture (HLA)—Framework and Rules, Standard 1516-2010*, Institute of Electrical and Electronics Engineers, New York, NY.

41. Institute of Electrical and Electronics Engineers. (2012). *IEEE Standard for Distributed Interactive Simulation—Application Protocols, Standard 1278.1-2012*, Institute of Electrical and Electronics Engineers, New York, NY.

About the Exploratory Advanced Research Program

FHWA's Exploratory Advanced Research (EAR) Program focuses on long-term, high-risk research with a high payoff potential. The program addresses underlying gaps faced by applied highway research programs, anticipates emerging issues with national implications, and reflects broad transportation industry goals and objectives.

To learn more about the EAR Program, visit the EAR Web site at www.fhwa.dot.gov/advancedresearch. The site features information on research solicitations, updates on ongoing research, links to published materials, summaries of past EAR Program events, and details on upcoming events.