



EXPLORATORY ADVANCED RESEARCH

# EAR Program Research Results

Updated through 2014



U.S. Department  
of Transportation  
**Federal Highway  
Administration**

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### **Cover photos**

*Left:* Computing and navigating instruments in the trunk of a project test vehicle, demonstrated at FHWA's Turner-Fairbank Highway Research Center (see pages 7, 8, and 9 and the report of an EAR Program-sponsored workshop on vehicle positioning at <http://www.fhwa.dot.gov/advancedresearch/pubs/13052/13052.pdf>).

*Right:* FHWA's Highway Driving Simulator, located at the Turner-Fairbank Highway Research Center, used in a project's comparison of results from four simulator platforms (see page 20).

# EAR Program Research Results

Exploratory Advanced Research . . .  
Next Generation Transportation Solutions

The Exploratory Advanced Research (EAR) Program addresses the need for longer term, higher risk research with the potential for long-term improvements to transportation systems—improvements in planning, building, renewing, and operating safe, congestion-free, and environmentally sound transportation facilities. The EAR Program seeks to leverage advances in science and engineering that could lead to breakthroughs for critical current and emerging issues in highway transportation—where there is a community of experts from different disciplines who likely have the talent and interest in researching solutions and who likely would not do so without EAR Program funding.

Broad scientific participation and extensive coverage of advanced ideas and new technologies are secured by engaging stakeholders throughout the EAR Program’s processes—not only in identifying and scoping topics, but also in ensuring the technical quality of sponsored research through expert panels and in communicating research results.

This catalog of results documents the output of that effort, a critical link in the chain of research, development, and deployment of new technology and practices necessary for the United States to have the best transportation system in the world for decades to come.

The EAR Program focuses investments in areas where changes in science and engineering can dramatically lead towards making the highway system safer, more durable, and more efficient:

- Connected Highway and Vehicle System Concepts.
- Breakthrough Concepts in Materials Science.
- Human Behavior and Travel Choices.
- New Technology and Advanced Policies for Energy and Resource Conservation.
- Technology for Assessing Performance.

## The Exploratory Advanced Research Program

The results of EAR Program-funded projects may include new fundamental insights and how they can be applied in highway transportation; new research methods, models, or data that can accelerate applied research; or new system concepts or prototypes, including laboratory testing and possibly limited field testing. The program does not fund projects through commercialization or deployment. Rather, results must be taken up by the research community, with the support of other funding sources. FHWA is committed to transitioning the results of EAR Program-funded projects and takes an active role in demonstrating results to audiences critical to continuing the research and development cycle.

Through eight solicitations, the EAR Program has awarded 75 projects (36 of which are ongoing as of September 2014) involving both government and academic researchers. These projects represent the investment of \$72 million in FHWA funds and leverage \$26 million in matching funds. Additional projects will be funded in 2015. The following pages contain summary descriptions of the results of selected recently completed research investigations.

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## Connected Highway and Vehicle System Concepts

**PROJECT:** Intersection Control for Autonomous Vehicles

**INSTITUTION:** University of Texas at Austin

**COMPLETED:** 2013

**OBJECTIVE:** To develop, test, and evaluate (in simulation with a full-size robotic vehicle) traffic control algorithms for autonomous intersection management (AIM) and autonomous vehicles.

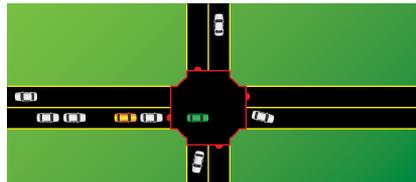
**CONTACT:** Gene M. McHale, FHWA Office of Operations R&D

**RESOURCES:** Project details at <http://www.fhwa.dot.gov/research/tfhrcc/projects/projectsdb/projectdetails.cfm?projectid=FHWA-PROJ-07-0026>

Research reports and simulation videos at <http://www.cs.utexas.edu/~aim/>

**RESULTS:** The project demonstrated that AIM, in conjunction with autonomous vehicles communicating with each other and with roadside equipment, can dramatically improve intersection efficiency, reduce traffic delays, and alleviate traffic congestion. The research team developed and tested traffic control algorithms for autonomous vehicles and evaluated them first in simulation only and then in simulation integrated with a full-size robotic vehicle. Among several important project innovations are the following:

- Parameters for an autonomous vehicle to safely cross an intersection in an AIM system.
- A setpoint-scheduling algorithm to control arrival time, velocity, and position of an autonomous vehicle by sending control parameters to its brake and throttle actuators.
- Prioritization schemes to allocate intersection access and keep traffic moving.
- A preemptive, fail-safe protocol to prevent collisions when mechanical failures occur.



An AIM simulation, which shows virtual and real vehicles at an intersection. White vehicles have a reservation to enter the intersection; yellow vehicles do not. The green vehicle is a proxy, representing the real-world location of the autonomous vehicle.

**IMPACT:** As automated vehicles come onto the market, results from this project have the potential to provide a safe system for improving traffic flow and dramatically reducing fuel use and mobile source emissions at intersections.



## Connected Highway and Vehicle System Concepts

**PROJECT:** **Advanced Traffic Signal Control Algorithms**

**INSTITUTIONS:** California Department of Transportation; California PATH, University of California, Berkeley; Center for Environmental Research and Technology, University of California, Riverside; BMW Group

**COMPLETED:** 2013

**OBJECTIVE:** To develop advanced signal control strategies based on connected vehicle data, that is, real-time information on a vehicle's location, speed, and characteristics, as well as communication to the signal control infrastructure.

**CONTACT:** **Peter Huang**, FHWA Operations R&D

**RESOURCES:** Project details at <http://www.fhwa.dot.gov/research/tfhrc/projects/projectsdb/projectdetails.cfm?projectid=FHWA-PROJ-10-0009>

Technical report at [http://www.ocf.berkeley.edu/~xuanyg/Argote\\_Christofa\\_Xuan\\_Skabardonis\\_2012\\_TRB.pdf](http://www.ocf.berkeley.edu/~xuanyg/Argote_Christofa_Xuan_Skabardonis_2012_TRB.pdf)

**RESULTS:** The research team developed and tested several signal control applications, including strategies to minimize the occurrence of red-light running. The team's prediction algorithm for DARE (dynamic all-red extension when a high probability of collision exists) achieved a correct detection and activation rate over 95 percent. Strategies to reduce arrival flow during the yellow interval, which influences red-light running in coordinated arterials, were also effective. To minimize fuel consumption, the team developed an in-vehicle speed advisory system that achieved fuel savings of over 13 percent in field tests. The team also proposed new methods for estimating common arterial measures of effectiveness for different penetration rates of connected vehicles. In one example, the team found that to accurately estimate intersection queue length in lighter traffic conditions, 80 percent of vehicles need to have connectivity, but in oversaturated conditions, only 10 percent need to be equipped. This finding indicates that connective traffic control strategies may be possible in the most congested networks before connected vehicles are ubiquitous.

**IMPACT:** The project results show great potential to advance real-time signal control strategies in some cases with low levels of new technology adoption. Improved efficiency will reduce travel time, frequency and length of stops, fuel consumption, and harmful emissions.



## Connected Highway and Vehicle System Concepts

**PROJECT:** **Advanced Freeway Merge Assistance:  
Harnessing the Potential of Connected Vehicles**

**INSTITUTION:** University of Virginia Center for Transportation Studies

**COMPLETED:** 2012

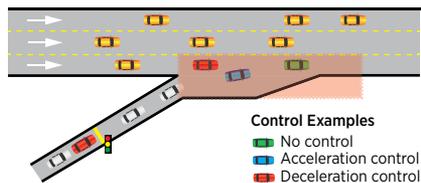
**OBJECTIVE:** To develop and evaluate candidate freeway merge assistance systems that might improve the efficiency and safety of freeway merges in a connected vehicle environment.

**CONTACT:** **Robert A. Ferlis**, FHWA Office of Operations R&D

**RESOURCE:** Project details and final report at <http://www.fhwa.dot.gov/research/tfhrc/projects/projectsdb/projectdetails.cfm?projectid=fhwa-proj-09-0066>

**RESULTS:** The project team developed four algorithms that use connected-vehicle data to improve freeway merging strategies: lane-level variable speed limit, lane-changing advisory, gap-responsive on-ramp signal, and merging control. The team evaluated the algorithms within a connected vehicle simulation environment that simulates both vehicle movement and communications. The lane-level variable speed limit approach, lane-changing advisory, and gap-responsive on-ramp signal algorithms did not produce statistically significant improvement, although they showed potential. The merge-control algorithm, however, generated statistically significant benefits in average speed (23.6 percent increase), travel time (11.5 percent decrease), delays (17.9 percent decrease), and miles traveled (2.4 percent increase) within the connected vehicle environment. A sensitivity analysis of market penetration rates revealed that significant system improvements occur when 50 percent or more vehicles have connective capabilities.

**IMPACT:** These results will help transportation agencies understand the value of connected vehicle technology as it emerges and may eventually lead to freeway merge areas with greater capacity and fewer crashes.



Freeway merge control example. Within the merging area, the acceleration of the vehicles is controlled: leading (green, no change), entering (blue, acceleration), and following (red, deceleration).



## Connected Highway and Vehicle System Concepts

**PROJECT:** **Next Generation Vehicle Positioning in GPS-Degraded Environments for Vehicle Safety and Automation Systems**

**INSTITUTIONS:** Auburn University, Kapsch TrafficCom, Pennsylvania State University, Stanford Research Institute

**COMPLETED:** 2012

**OBJECTIVE:** To provide ubiquitous, precise positioning in regard to vehicle safety and automation in the presence of Global Positioning System (GPS) degradation.

**CONTACT:** **David Gibson**, FHWA Office of Operations R&D

**RESOURCES:** Final report, presentations, and video at [http://www.eng.auburn.edu/~dmbevly/FHWA\\_AU\\_EAR2/](http://www.eng.auburn.edu/~dmbevly/FHWA_AU_EAR2/)

Project details at <http://www.fhwa.dot.gov/research/tfhrc/projects/projectsdb/projectdetails.cfm?projectid=FHWA-PROJ-09-0061>

**RESULTS:** The project team developed an integrated vehicle positioning system in which subsystems with complementary strengths are fused to provide precise positioning data in environments where one or more of the subsystems could fail. The subsystems assessed were GPS, inertial navigation systems (INS), camera and LIDAR lane departure warning systems, a dedicated short-range communications distance estimation system, visual odometry, and a road fingerprinting system. The accuracy and robustness of integrated systems were evaluated in test track and roadway scenarios under various weather conditions and at various speeds. The subsystems helped to improve lane-level accuracy. In live tests, GPS/INS integration provided improved results over standalone GPS, particularly in heavy foliage and urban canyon environments, and the full system of sensors performed best overall.



Camera and LIDAR equipment mounted on the roof of the test vehicle.

**IMPACT:** New algorithms, data fusion techniques, and ways of handling GPS data discovered in the project can support major improvements in vehicle positioning performance. Data fusion techniques can produce low-cost, precise positioning, allowing for a range of safety and mobility applications that currently would require high-cost equipment.



## Connected Highway and Vehicle System Concepts

**PROJECT:** Innovative Approaches for Next Generation Vehicle Positioning

**INSTITUTION:** University of California, Riverside

**COMPLETED:** 2012

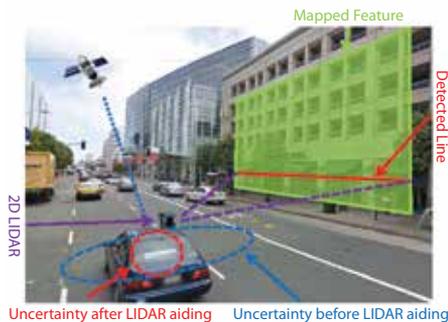
**OBJECTIVE:** To investigate and test a range of approaches that could provide lane-level positioning accuracy in diverse driving environments.

**CONTACT:** Mohammed Yousuf, FHWA Office of Operations R&D

**RESOURCE:** Project details at <http://www.fhwa.dot.gov/research/tfhrcc/projects/projectsdb/projectdetails.cfm?projectid=FWHA-PROJ-09-0062>

**RESULTS:** No single positioning technology can meet the requirements for lane-level positioning across diverse driving environments—each has performance limitations. This project explored the most promising technologies for improving the accuracy, availability, and reliability of vehicle positioning by augmenting Global Navigation Satellite System/Inertial Navigation System technology. After evaluating the performance of aiding technologies (LIDAR, radar, computer vision, and dedicated short-range communication (DSRC)), the research team developed and tested prototype systems that integrate a variety of sensors. The team found that LIDAR and radar technology integrate with the quickest processing and response, and terrestrial radio navigation and DSRC methods require more time. Radio and DSRC-based methods show great promise because implementation costs are relatively low, but require further development to improve accuracy. The performance of vision-based aiding improves with increased sensor cost; however, implementation requires development of onboard feature mapping.

**IMPACT:** This project's theoretical and experimentally demonstrated results will facilitate continued rapid advancement in vehicle positioning technology, providing opportunities for new safety, mobility, and eco-drive applications.



Typical use of two-dimensional LIDAR to aid positioning in urban areas.



## Connected Highway and Vehicle System Concepts

**PROJECT:** **Development of Enhanced Safety Systems Based on GPS/INU System**

**INSTITUTIONS:** Ohio State University, University of Virginia, DGSS Solutions, LLC

**COMPLETED:** 2012

**OBJECTIVE:** To test emerging navigation technologies in a simulation environment that could lead to better assessment of future navigation technology and improved methods for roadway design.

**CONTACT:** **Mohammed Yousuf**, FHWA Office of Operations R&D

**RESOURCE:** “Integrated GNSS/INU, Vehicle Dynamics, and Microscopic Traffic Flow Simulator for Automotive Safety,” *Proceedings, 14th International IEEE Conference on Intelligent Transportation Systems*, 2011, at <http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6082995>

**RESULTS:** The project team developed an integrated simulation platform to evaluate the impact of emerging vehicle positioning and communications technologies that provide level positioning at less than 10 cm (3.9 in) and allow connected vehicles and infrastructure to monitor and share safety-related information. To estimate how system errors, communication delays, and communication interruptions affect the timing of warnings, driver perceptions/reactions, network-wide delays, and safety, the team simulated warning scenarios for eight sensor system combinations. The team found that error- and delay-free driver warnings reduce the number of conflicts in the range of 28 percent to 50 percent. The project compared different positioning approaches for overall accuracy and for providing the fewest false and missing warnings.

**IMPACT:** Use of the integrated simulation environment to assess connected vehicle technologies and improve roadway design can reduce the risk of crashes, prevent travel delays, and reduce fuel consumption as new systems are implemented.



## Connected Highway and Vehicle System Concepts

**PROJECT:** **Development and Evaluation of Selected Mobility Applications for VII**

**INSTITUTIONS:** California PATH, University of California, Berkeley; California Department of Transportation

**COMPLETED:** 2011

**OBJECTIVE:** To develop new strategies to reduce bottlenecks, minimize congestion, and maximize throughput by utilizing the capabilities of intelligent vehicles and highway infrastructure.

**CONTACT:** **Robert A. Ferlis**, FHWA Office of Operations R&D

**RESOURCES:** Final report at [http://www.dot.ca.gov/newtech/researchreports/reports/2011/task\\_2138-tsm.pdf](http://www.dot.ca.gov/newtech/researchreports/reports/2011/task_2138-tsm.pdf)  
Project Web site at [http://gateway.path.berkeley.edu/~xylyu/files/Truck\\_Control.html](http://gateway.path.berkeley.edu/~xylyu/files/Truck_Control.html)

**RESULTS:** The project team modeled, tested, and demonstrated prototype wireless communication systems to improve traffic flow by calculating and communicating variable speed limits (VSL) to drivers; achieve higher effective lane capacities using cooperative adaptive cruise control (CACC); and reduce fuel consumption and increase truck-only lane capacity with automated platoons.

*Variable Speed Limits*—In simulation and live tests on I-80, the researchers broadcast speeds calculated to prevent traffic flow breakdowns, with promising results. VSLs show significant potential to prevent traffic delays.

*Cooperative Adaptive Cruise Control*—Study results show that CACC could substantially increase highway capacity when it reaches moderate to high market penetration. Retrofitting non-CACC vehicles with inexpensive “here I am” radios could accelerate achievement of these capacity benefits.

*Automated Truck Platoon Control*—A wireless communications system successfully coordinated a platoon of three tractor-trailer trucks traveling at 85 km/h (53 mi/h) and in varied joining and splitting maneuvers. Fuel savings were estimated at 10 to 14 percent for the following trucks.

**IMPACT:** New connected vehicle and highway systems can lead to substantial safety, operational, and environmental benefits.



## Connected Highway and Vehicle System Concepts

**PROJECT:** Layered Object Recognition System for Pedestrian Collision Sensing

**INSTITUTIONS:** Sarnoff Corporation, AutoLiv Electronics America

**COMPLETED:** 2009

**OBJECTIVE:** To develop a real-time, in-vehicle, vision-only system to detect pedestrians and determine potential collisions with high accuracy and minimal false alarms.

**CONTACT:** Wei Zhang, FHWA Office of Safety R&D

**RESOURCES:** Conference paper at <http://onlinepubs.trb.org/onlinepubs/conferences/2011/RSS/2/Zhang,W.pdf>

Final report at <http://www.fhwa.dot.gov/publications/research/safety/11056/11056.pdf>

**RESULTS:** The project team developed an in-vehicle, stereo vision-based system that detects, recognizes, and tracks pedestrians in its field of view. The system uses contextual information to reduce false alarms and light-enhancing techniques to improve low-visibility detection. Evaluated on publicly available datasets, the system matched or exceeded the performance of leading pedestrian detectors, tracking pedestrians at vehicle speeds of up to 48 km/h (30 mi/h) and distances up to 35 m (115 ft) away under good visibility conditions and up to 25 m (82 ft) away under reduced visibility with a 90-percent overall positive detection rate. The researchers recommend further development to upgrade performance. The feasibility of commercial implementation is high, since the system uses low-cost components.

**IMPACT:** Twilight hours are the most dangerous time for pedestrians. Existing detection systems, however, have limited effectiveness in low-light conditions. New approaches introduced in this study provide superior results in twilight.



Visual output of the pedestrian-detection system as it recognizes crossing pedestrians.



## Breakthrough Concepts in Material Science

**PROJECT:** **Greatly Increased Use of Fly Ash in Hydraulic Cement Concrete for Pavement Layers and Transportation Structures**

**INSTITUTIONS:** Purdue University, Auburn University, National Institute of Standards and Technology, National Ready Mixed Concrete Association, FHWA's Chemistry and Concrete Laboratories

**COMPLETED:** 2012

**OBJECTIVE:** To improve understanding of infrastructure materials, specifically, how to use higher amounts of fly ash in concrete and obtain the performance needed for long-lasting concrete highway pavements and structures.

**CONTACT:** **Richard C. Meininger**, FHWA Office of Infrastructure R&D

**RESOURCES:** Final report at [http://www.nrmca.org/research\\_engineering/Documents/Lab\\_fly\\_ashFinal\\_report.pdf](http://www.nrmca.org/research_engineering/Documents/Lab_fly_ashFinal_report.pdf)  
Presentation at <http://webpages.mcgill.ca/staff/Group3/aboyd1/web/Conferences/AMW%20XI/Presentations/Meininger%20Rev.pdf>

**RESULTS:** Large-scale experiments demonstrated that high-volume fly ash (HVFA) concrete can be produced to have setting times and early-age compressive strength development comparable to conventional portland cement concrete. In experiments with HVFA replacement volumes of 40 percent and 60 percent, researchers found that lower water-to-cementitious materials ratios



Fly ash with different carbon content levels.

and internal curing (adding pre-wetted lightweight aggregates that release water to the matrix after time of set) improved early-age strength and reduced early-age cracking. Other project studies examined materials compatibility, prediction methods for property development, improved freezing and scaling durability, and activation energy values of cementitious materials. Technology transfer activities in the project will guide agencies and contractors in using HVFA in concrete mixtures.

**IMPACT:** The performance data and best practices flowing from this project can lead to significantly increased use of fly ash in concrete mixtures, resulting in transportation infrastructure with a smaller carbon footprint, lower embodied energy, and improved long-time performance.



## Breakthrough Concepts in Material Science

**PROJECT:** **High-Performance Stress-Relaxing Cementitious Composites for Crack-Free Pavements and Transportation Structures**

**INSTITUTIONS:** Texas A&M University, Texas Transportation Institute

**COMPLETED:** 2011

**OBJECTIVE:** To achieve a durable concrete with enhanced viscoelastic properties and high resistance to cracking through the utilization of nano inclusions.

**CONTACT:** **Richard C. Meininger**, FHWA Office of Infrastructure R&D

**RESOURCES:** Technical report at <http://d2dtl5nnlpr0r.cloudfront.net/swutc.tamu.edu/publications/technicalreports/476660-00017-1.pdf>  
Research article at <http://www.hindawi.com/journals/jnm/2012/371927>

**RESULTS:** Investigators performed a comprehensive review of previous work using carbon nanofilaments (CNFs) and tubes (CNTs) in cementitious materials to improve their mechanical properties and behaviors, and conducted a detailed study of the common method of incorporating CNFs. They developed a novel thermodynamic-based dispersion quantification method to measure the effect of geometry-dependent clustering on CNF dispersion in cement paste. They also developed a new method for improving and stabilizing CNF dispersion in cement paste using silica fume to significantly improve CNF dispersion in a hardened cementitious matrix. Finally, experimental investigation of the effect of CNFs on the mechanical behavior and properties of hardened cement paste showed that CNFs can increase flexural strength and reduce shrinkage cracking. The researchers produced an advanced hardened cement paste that is strong and resists shrinkage cracking quite well under certain levels of restraint. Next steps could include additional exploratory advanced research.

**IMPACT:** Use of new materials such as CNTs can lead to increased durability of pavements and structures as well as to multifunctional materials such as self-sensing pavements.



## Human Behavior and Travel Choices

**PROJECT:** **Multimodal Connectivity Options for a Future Seamless Transportation System**

**INSTITUTION:** University of Southern California

**COMPLETED:** 2014

**OBJECTIVE:** To harness emerging technologies to develop a new type of decentralized transportation system based on a market for unused transportation capacity.

**CONTACT:** **Jeremy Raw**, FHWA Office of Planning, Environment, and Realty

**RESOURCE:** Project details at <http://www.fhwa.dot.gov/research/tfhrc/projects/projectsdb/projectdetails.cfm?projectId=FHWA-PROJ-11-0049>

**RESULTS:** The research team explored how to bring unused transportation capacity (i.e., empty seats in vehicles already making certain types of trips) to a novel market that is able to match riders and drivers, negotiate a fair price for transport, and efficiently adjust routes so as to preserve benefits for all users. The research team explored computational and algorithmic issues related to pricing and route allocation in dynamic ridesharing systems, and developed important innovations that have been documented in several academic publications. Building on their basic research, the team developed open-source simulation software that can perform ride matching, routing, and auction pricing. The research team also conducted a workshop on car sharing and dynamic ridesharing to discuss the state of practice and knowledge in this area.

**IMPACT:** Understanding and simulating the market mechanisms and dynamics of shared ride transportation based on small financial transactions will support continued growth and innovation in this rapidly evolving transportation market. The open-source software is freely available so that it can serve as a platform for further research in this area.



## Human Behavior and Travel Choices

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

**INSTITUTION:** University of Maryland

**COMPLETED:** 2014

**OBJECTIVE:** To develop a theoretical framework for agent-based driver and traveler behavior modeling.

**CONTACT:** **Brian Gardner**, FHWA Office of Planning

**RESOURCE:** Project details at <http://www.fhwa.dot.gov/research/tfhrc/projects/projectsdb/projectdetails.cfm?projectid=FHWA-PROJ-11-0028>

**RESULTS:** The research team developed a theoretical framework for agent-based driver and traveler behavior modeling. The team evaluated traditional and emerging data collection methods for ABMS in transportation, evaluated alternative implementation platforms for ABMS applications in transportation, and developed an agent-based model of en-route and pre-trip route, departure time, and mode choices. The model considers five key ABMS components: (1) agent characteristics, (2) agent behavior rules, (3) observable agent behavior, (4) agent experience, and (5) attributes of the environment. A key factor of the integrated model is a learning process that allows cumulative agent experiences to lead to changes in certain agent preferences and subsequent decisions. The research team demonstrated the concept in the Washington, DC—Baltimore region, where additional data was collected for agent behavior estimation and validation. The model was used to evaluate traffic and regional demand impacts of Maryland's Inter-County Connector project and the I-270 multimodal corridor traffic management strategies.

**IMPACT:** The results from this research project will help understand future demand travel needs, improve transportation system management and travel reliability, and provide valuable investment insight for maintaining urban transport systems and services in the Washington, D.C.—Baltimore region. More broadly, the model demonstrates the potential of ABMS for improved forecasting accuracy, improved understanding of driver and traveler behavior, and modeling of transportation systems management concepts and insights for capital investment.



## Human Behavior and Travel Choices

**PROJECT:** **Evolutionary Agent System for Transportation Outlook (VASTO)**

**INSTITUTIONS:** University of Arizona; George Mason University

**COMPLETED:** 2014

**OBJECTIVE:** To use agent-based modeling and simulation to examine driver behavior and interactions between travelers, vehicles, and traffic management centers.

**CONTACT:** **David Yang**, FHWA Office of Safety R&D

**RESOURCES:** Project details at <http://www.fhwa.dot.gov/research/tfhr/projects/projectsdb/projectdetails.cfm?projectid=FHWA-PROJ-11-0040>

**RESULTS:** The research team used computational and algorithmic advances in other areas as an opportunity to improve existing transportation analysis capabilities. The team developed a theoretically sound, behaviorally robust, and computationally efficient transportation analysis modeling system that seamlessly integrates the concepts of agent-based modeling with existing and emerging simulation tools. The researchers delivered a set of comprehensive modeling tools and a revolutionary system for a multi-agent system modeling framework. The modeling system incorporates innovative ideas in the area of agent-based modeling to model agents such as drivers and traffic management centers. This research project provides fundamental knowledge on how agent-based modeling and simulation can be useful for transportation system analysis and has developed open-source computer programs for other researchers to use.

**IMPACT:** This research transforms the understanding and modeling of the interactions among heterogeneous agents that represent various groups of a transportation system. It advances the ability to realistically mimic various behaviors in a computer-simulated transportation network and examine their impacts. It will ultimately aid decision making on transportation investments and contribute to effective management strategies; leading to a safer, more efficient transportation system.



## Human Behavior and Travel Choices

**PROJECT:** **Machine Learning for Automated Analysis of Large Volumes of Highway Video**

**INSTITUTION:** Carnegie Mellon University/National Robotics Engineering Center

**COMPLETED:** 2014

**OBJECTIVE:** To automate feature extraction from the very large quantities of video data produced by the second Strategic Highway Research Program's (SHRP 2's) Naturalistic Driving Study (NDS).

**CONTACT:** **Lincoln Cobb**, FHWA Office of Safety R&D

**RESOURCE:** Project details at <http://www.fhwa.dot.gov/research/tfhrc/projects/projectsdb/projectdetails.cfm?projectid=FHWA-PROJ-12-0070>

**RESULTS:** Feature extraction from highway video has traditionally been an essentially manual process. Technicians scroll through the video files, noting where features of interest are identified; however, the data collected by the SHRP 2 project totals over 1-million hours of video, rendering manual feature extraction unfeasible. In this project the research team developed a multipurpose software framework for analysis of very large volumes of video data and demonstrated several feature detection and classification algorithms for archived on-road video datasets. The research team built on previous experience using machine learning and image processing to detect vehicles and navigate urban and off-road environments. This resulted in the development of powerful and flexible methods for analyzing very large amounts of video data collected on roads and highways. Combined with large-scale image processing techniques, the ultimate goal is for researchers to be able to automatically search through enormous datasets, such as the SHRP 2 NDS data, and identify features of interest to safety researchers. This work also identified possible approaches to feature extraction from comparatively poor quality video data.

**IMPACT:** This project demonstrates the effectiveness of advanced machine-learning techniques applied to large, diverse datasets. The research lays the groundwork for future development of a comprehensive library of data processing and analysis tools and will ultimately make it easier and faster to study large-scale datasets and extract information from them.



## Human Behavior and Travel Choices

**PROJECT:** Design of a Completely New Approach for a National Household-Based Long Distance Travel Survey Instrument

**INSTITUTIONS:** Batelle; The Urban Institute; University of Maryland

**COMPLETED:** 2013

**OBJECTIVE:** To identify and assess novel, innovative techniques and methods that can yield improved estimates in future FHWA long-distance household travel surveys.

**CONTACT:** Patrick Zhang, FHWA Office of Highway Policy Information

**RESOURCES:** Project details at <http://www.fhwa.dot.gov/research/tfhrc/projects/projectsdb/projectdetails.cfm?projectid=FHWA-PROJ-11-0044>

**RESULTS:** This research project investigated alternative ways to capture long-distance travel behavior in an accurate, scientifically rigorous, and cost-effective manner. The research team developed and tested new smartphone and Facebook applications to passively detect when a survey participant has taken a long-distance trip and then prompt that individual for trip-related information through an online survey. These applications were successfully tested in a pilot study involving over 250 individuals. The research team also developed and tested a series of post-processing methods (based on machine-learning techniques) that estimate trip purpose for long-distance travel as a function of available travel survey data and other supplementary data. This approach could ultimately impact the design of future long-distance travel surveys by reducing the burden placed on collecting data directly from respondents through questionnaires.

**IMPACT:** This project led to several key recommendations for an efficient yet scientific-based design, implementation, and processing of the next nationally-representative travel survey that specifically addresses long-distance travel behavior.



## Human Behavior and Travel Choices

**PROJECT:** Making Driving Simulators More Useful for Behavioral Research

**INSTITUTIONS:** University of Iowa/National Advanced Driving Simulator; University of Wisconsin; Western Transport Institute, Montana State University; Battelle; Entropy Control, Inc.; William H. Levison Associates

**COMPLETED:** 2013

**OBJECTIVE:** To develop a mathematical transformation that will allow scientists and engineers to better predict the behavior of drivers in real environments based on the results of experiments conducted in driving simulators.

**CONTACT:** Brian Philips, FHWA Office of Safety R&D

**RESOURCE:** Project details at <http://www.fhwa.dot.gov/research/tfhrc/projects/projectsdb/projectdetails.cfm?projectid=FHWA-PROJ-09-0067>

**RESULTS:** The research team identified highway design needs and matched them to specific characteristics of driving simulators (e.g., motion, field of view, speed, and steering torque) and developed and demonstrated tools to characterize how closely responses to simulator characteristics match real-

world driving outcomes. In experiments conducted on four different simulator platforms, the researchers compared driver judgment of simulator fidelity and performance in virtual roadway scenarios and found little effect of motion and a moderate effect of visual complexity. The results show that using a high-fidelity simulator, with attention to accurately rendering the visual complexity of the roadway, will lead drivers in the simulator to drive at speeds quite comparable to those observed on actual roadways.



Actual road data (red points) used in response comparisons for a roundabout scenario.

**IMPACT:** Models developed in this project will enable the driving safety research community and highway designers to predict real-world driving behavior more accurately from behavior in driving simulators and to integrate the results from different simulators more readily. The models also will better indicate to researchers when experiments require high fidelity simulation and when lower fidelity approaches are adequate, thereby saving time and funding on future studies.



## Human Behavior and Travel Choices

**PROJECT:** Behavioral Sciences Approach to Testing, Validating, and Establishing Best Practices for Alternative Highway Revenue Collection

**INSTITUTIONS:** University of Central Florida and Georgia State University

**COMPLETED:** 2013

**OBJECTIVE:** To understand drivers' behavioral choices between tolled and "free" routes and choices of departure time by estimating risk attitudes, accuracy of risk perception, and discount rate.

**CONTACT:** Karen White, FHWA Office of Transportation Policy Studies

**RESOURCES:** Study summary at <http://www.fhwa.dot.gov/advancedresearch/pubs/congestion/index.cfm>

Presentation at <http://www.transportationeconomics.org/meetings>—open the link "An Experimental Economics Investigation into Responses to Congestion Pricing, Harb."

**RESULTS:** To improve understanding of when and why drivers choose a tolled facility, the research team used experimental economics with a population of local drivers and students participating in (1) stylized lotteries to reveal risk attitudes; (2) driving simulators to reveal risk attitudes and travel time perceptions; and (3) GPS-recorded actual driving choices. More than 550 drivers with residence and workplace connected by both a toll and a "free" route participated in Orlando, Florida, and Atlanta, Georgia. They responded to varying road prices in actual driving and simulations to assess their risk attitudes and travel time biases in response to monetary incentives. In another experiment, 210 college students participated in driving simulations of route choices to test whether their behavior could predict field driver behavior. The study concludes that risk attitudes are comparable across tasks and regions, and in college students versus field drivers. The researchers found evidence of risk aversion as captured both by sensitivity over values of route choices and by pessimism over likelihoods of congestion.

**IMPACT:** Currently revenue projections for priced roadways are based on methods with limited accuracy, which can result in projects with lower than expected revenue. The results of this research confirm the importance of accurately incorporating risk attitudes in policy analysis and impact assessment of congestion pricing. The use of less-costly subject pools and instruments to gather behavioral data as demonstrated in the project can increase opportunities to investigate driver choices and incorporate more accurate data when determining potential revenue.



## Human Behavior and Travel Choices

**PROJECT:** **Effects of Automated Transit and Pedestrian/Bicycling Facilities on Urban Travel Patterns**

**INSTITUTIONS:** University of Michigan, University of Illinois at Chicago

**COMPLETED:** 2013

**OBJECTIVE:** To evaluate whether innovative pedestrian, bicycle, and transit facilities and services will attract travelers and decrease passenger car travel.

**CONTACT:** **Robert A. Ferlis**, FHWA Office of Operations R&D

**RESOURCE:** Project details at <http://www.fhwa.dot.gov/research/tfhrc/projects/projectsdb/projectdetails.cfm?projectid=FHWA-PROJ-09-0037>

**RESULTS:** Researchers in this project found that high-frequency shuttle service between a neighborhood and a regional rail transit system with available capacity can have a significant effect on choice of travel mode. The researchers conducted a household survey in four metropolitan Chicago communities to assess whether community shuttle service, bike lanes, walkway improvements, and other amenities would increase use of rail transit. In each neighborhood, they queried 150 residents who lived within 1.5 mi (2.4 km) of a rail transit station and worked within 3 mi (4.8 km) of a station on their current travel patterns and mode preferences under the hypothetical improvements. Simulations using a combination agent-based/activity-based model predicted that neighborhood shuttle service combined with bike lanes would decrease car use from 36 percent to 22 percent and increase rail transit use from 50 percent to 67 percent. Predicted shifts to rail were higher in lower density communities with lower rail use.

**IMPACT:** The project's results support the value of continued research into automating high-frequency shuttle services to help reduce traffic congestion, fuel consumption, and greenhouse gas emissions.



## Human Behavior and Travel Choices

**PROJECT:** Megaregional Travel

**INSTITUTIONS:** University of Maryland, National Center for Smart Growth; ECONorthwest; Parsons Brinckerhoff; LEAM Group, University of Illinois at Urbana/Champaign; and David Simmonds Consultancy

**COMPLETED:** 2013

**OBJECTIVE:** To develop methods and tools that support planning for the Nation's megaregions, integrating multiple disciplines, travel modes, and geographic levels.

**CONTACT:** Supin Yoder, FHWA Office of Planning

**RESOURCES:** Report at [http://www.pbworld.com/pdfs/pb\\_in\\_the\\_news/moeckel\\_weidner\\_et\\_al\\_trb2012\\_mega-region\\_framework\\_analyzing\\_high\\_energy\\_price\\_future.pdf](http://www.pbworld.com/pdfs/pb_in_the_news/moeckel_weidner_et_al_trb2012_mega-region_framework_analyzing_high_energy_price_future.pdf)

Case study at <http://www.fhwa.dot.gov/planning/megaregions/reports/>

**RESULTS:** Megaregions, large agglomerations of metropolitan areas, represent a development pattern spreading across the world and a new planning geography. In this project, researchers developed and demonstrated the Megaregion Market Analysis Framework, which contains a market analysis and analytic tools. The market analysis focuses on defining the megaregion's boundaries, identifying issues it must address, and describing its characteristics. The analytic tools—an economic model linked with a travel demand model—enable analysis of the intricate effects of economic changes on a megaregion's economy and transportation system. Applying this framework, the project defined the Chesapeake megaregion and used existing models and data to identify its issues and characteristics. The market analysis illustrates the need to broaden the planning perspective beyond local and metropolitan areas.

**IMPACT:** This project provides the framework and tools for policy makers to understand issues such as freight and the economy on a megaregional scale and demonstrates that analytic tools can be developed with available data and at reasonable cost for megaregional analysis.



## Human Behavior and Travel Choices

**PROJECT:** **Driver Behavior in Traffic**

**INSTITUTIONS:** Virginia Polytechnic Institute and State University, PTV America, Virginia Center for Transportation Innovation and Research

**COMPLETED:** 2012

**OBJECTIVE:** To characterize driver behavior using naturalistic driving data and agent-based modeling techniques for development of effective strategies to improve transportation safety and operations.

**CONTACT:** **David Yang**, FHWA Office of Safety R&D

**RESOURCE:** Final report at <http://www.ntis.gov>. Search: PB2012-105330.

**RESULTS:** This research provides a foundation for agent-based modeling of driver behavior based on naturalistic data through an integrated framework for safety and operation analysis. Lateral vehicle action was simulated in a microscopic traffic behavior modeling environment, bringing new insights to the modeling of driver maneuvering behavior during safety-critical events. Agents developed and evaluated in the VISSIM simulation platform revealed a close resemblance to real driver data. The project team improved car-following models through development of a hybrid model for greater accuracy and flexibility and through the addition of the new “passing and hook-following” thresholds. They used the model to simulate vehicle actions in safety-critical events, developed agent-based simulation components integrated with the VISSIM simulation package through its driver model, and developed and implemented a robust activation mechanism for agent-based simulation based on discriminant analysis. The investigators also identified key future research issues: adaptability of agents in real time and human factors issues related to warning individual drivers about changes in their driving behavior that might lead to safety-critical events.

**IMPACT:** New behavioral models are necessary to predict the safe and efficient use of new connected vehicle and roadside technology. This project demonstrates the ability of agent-based models based on naturalistic driving studies to create new and improved behavioral models.



## Human Behavior and Travel Choices

**PROJECT:** **Modeling the Urban Continuum in an Integrated Framework: Location Choice, Activity-Travel Behavior, and Dynamic Traffic Patterns**

**INSTITUTIONS:** Arizona State University, University of Arizona, University of Washington

**COMPLETED:** 2012

**OBJECTIVE:** To develop a conceptual framework, integrated prototype, and computational tools for modeling interactions between the built environment and multimodal transportation systems and for modeling urban systems across simulated land use, travel demand, and traffic flow.

**CONTACT:** **Brian Gardner**, FHWA Office of Planning, Environment, & Realty

**RESOURCE:** Project Web site at <http://urbanmodel.asu.edu/intmod.html>

**RESULTS:** SimTRAVEL, developed in this project, is an integrated modeling system that advances land-use and transportation microsimulation by providing seamless modeling of longer term choices about location (home, work, school) and shorter term choices of activity, travel mode, and route. SimTRAVEL integrates the use of UrbanSim (a land-use model), OpenAMOS (an activity-based microsimulation model), PopGen (a state-of-the-art synthetic population generator), and DynusT/MALTA (a dynamic traffic assignment and microsimulation model) within a behaviorally robust framework. The integrated systems have been fully implemented in a user-friendly software environment with powerful graphical user interfaces and visualization dashboards. Open-source software architecture with multithreading and parallel-computing capabilities speeds the simulations. SimTRAVEL was successfully tested and validated on a 500,000 population subregion of Maricopa County, Arizona.

**IMPACT:** The innovations in this modeling software, which is freely available to the modeling community, are expected to have a major impact on transportation planning for sustainable futures.



## Technology for Assessing Performance

**PROJECT:** Nanoscale Sensors for Structural Health

**INSTITUTION:** Georgia Institute of Technology

**COMPLETED:** 2013

**OBJECTIVE:** To develop and field-test the use of wireless, self-powered nanosensors and nanosensor arrays for real-time, autonomous strain and crack monitoring of steel bridges and other structures.

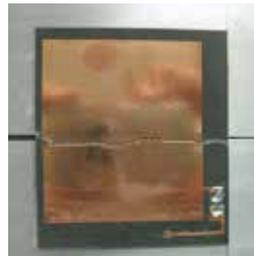
**CONTACT:** Hamid Ghasemi, FHWA Office of Infrastructure R&D

**RESOURCES:** “Passive Wireless Antenna Sensor for Strain and Crack Sensing—Electromagnetic Modeling, Simulation, and Testing,” *Smart Materials and Structures*, vol. 22, p. 085009, 2013, at <http://iopscience.iop.org/0964-1726/22/8/085009/>.

“Passive Wireless Smart-Skin Sensor Using RFID-based Folded Patch Antennas,” *International Journal of Smart and Nano Materials*, vol. 2, pp. 22–38, 2011, at <http://www.tandfonline.com/doi/full/10.1080/19475411.2010.545450#preview>.

Project details at <http://www.fhwa.dot.gov/research/tfhrc/projects/projectsdb/projectdetails.cfm?projectid=fhwa-proj-10-0014>

**RESULTS:** The research team has developed several types of wireless, self-powered, low-cost antenna sensors that can monitor potentially dangerous cracks in steel bridges. To reduce the costs of large-quantity production, multiple sensors are printed with inkjet printers and nanoscale conductive inks onto a thin, flexible film that can be applied to fatigue-prone areas of a bridge. The sensors create a network that can detect and measure multiple small cracks in proximity and their propagation. Powered by solar cells or energy captured from the signals of a wireless reader, the antenna sensor systems have great potential for low-cost, large-scale monitoring of transportation structures.



Antenna sensor tracking crack propagation.

**IMPACT:** The research results demonstrate the potential for designing low-cost, advanced strain-sensing systems that can improve the efficiency of maintenance and repair for steel bridges, provide substantial savings in operations, and increase safety.



## Technology for Assessing Performance

**PROJECT:** Flexible Skin Areal Shear Stress and Pressure Sensing System for Experimental Bridge Scour Research

**INSTITUTIONS:** National Aeronautics and Space Administration Jet Propulsion Lab and FHWA's J. Sterling Jones Hydraulics Research Laboratory

**COMPLETED:** 2011

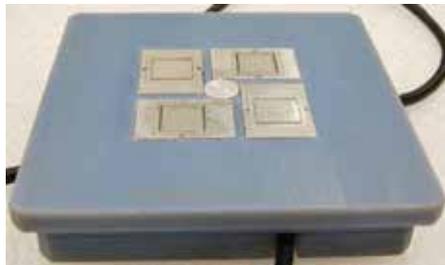
**OBJECTIVE:** To advance technology for measuring and understanding the complex flow fields and boundary shear stresses and pressure fields associated with bridge pier scour.

**CONTACT:** Kornel Kerenyi, FHWA Office of Infrastructure R&D

**RESOURCE:** Technical report at <http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/41997/1/11-0813.pdf>

**RESULTS:** In this project, the Jet Propulsion Laboratory conducted research on an integrated, flexible-skin, areal shear- and pressure-sensor system in a miniaturized array that measures changes in shear stress and pressure associated with scour-hole formation. The sensor elements were intended to measure shear forces in the range of 0.05 to 6 Pa and variations in pressure in the range of 0 to  $\pm 100$  Pa, with a sampling rate of more than 500 data points per second. Such a system will help researchers understand erosive flow mechanisms related to turbulence structures, together with local flow convergence and contractions around the fronts and flanks of piers or between piles of complex pier configurations. Direct measurements of shear forces are essential to validated computational fluid dynamic models.

**IMPACT:** Scour is the predominate cause of failure in bridges over water. The ability to capture shear stress and pressure data will significantly aid small-scale scour experiments in bridge scour research.



The flexible (skin) sensing system is based on an elastically mounted, floating plate concept. A single pressure sensor was inserted in the middle of this array. The optical encoder of each shear force sensor is encapsulated so the assembled sensor can be immersed in water.



## Technology for Assessing Performance

**PROJECT:** Development of Stiffness Measuring Device for Pad Foot Roller Compaction

**INSTITUTIONS:** Colorado School of Mines, with Caterpillar Inc., BOMAG, and the Colorado Department of Transportation

**COMPLETED:** 2011

**OBJECTIVE:** To develop a methodology to achieve continuous, real-time sensing of soil properties during static compaction with a pad foot roller.

**CONTACT:** Mike Adams, FHWA Office of Infrastructure R&D

**RESOURCES:** Poster presentation at [http://smartgeo.mines.edu/upload/poster\\_soil.pdf](http://smartgeo.mines.edu/upload/poster_soil.pdf)

Conference paper at <http://control.mines.edu/mooney/docs/RealTimeSoilCompactionMonitoringPadStrain.pdf>

**RESULTS:** Measurement of soil stiffness during compaction of foundations for highway structures is critical to ensuring that design-life specifications are met. In this study, investigators developed a conceptual framework for determining pad-soil contact force and displacement (and thus soil stiffness) from sensors built into the pads and roller, constructed a prototype measurement system, and devised a wireless data acquisition system to enable field-scale testing. They successfully measured plastic and elastic soil deformation during compaction using laser-based distance sensors and pad-strain-based techniques. Laboratory and field testing confirmed the predicted strain field changes. Some elements of the model need further refinement to ensure repeatable and accurate measurement across various soil conditions.

**IMPACT:** Intelligent compaction allows 100 percent quality control in real time. More comprehensive, accelerated measurement of compaction could improve long-term performance of roadway base courses and extend pavement life.



Strain gages, installed within selected pads that are welded to the drum, are wired to a signal processing box that transmits data wirelessly to a computer in the cab.

## **GETTING INVOLVED WITH THE EAR PROGRAM**

To take advantage of a broad variety of scientific and engineering discoveries, the EAR Program involves both traditional stakeholders (State department of transportation researchers, University Transportation Center researchers, and Transportation Research Board committee and panel members) and nontraditional stakeholders (investigators from private industry, related disciplines in academia, and research programs in other countries) throughout the research process.

## **LEARN MORE**

For more information, see the EAR Program Web site at [www.fhwa.dot.gov/advancedresearch](http://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.

## **EAR PROGRAM RESULTS**

The EAR Program strives to develop partnerships with the public and private sectors because the very nature of EAR is to apply ideas across traditional fields of research and stimulate new approaches to problem solving. The program bridges basic research (e.g., academic work funded by National Science Foundation grants) and applied research (e.g., studies funded by State departments of transportation). In addition to sponsoring EAR projects that advance the development of highway infrastructure and operations, the EAR Program is committed to promoting cross-fertilization with other technical fields, furthering promising lines of research through dissemination and continued investigations, and deepening vital research capacity.