



EXPLORATORY ADVANCED RESEARCH

# EAR Program Research Results

Updated through 2018



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

## EAR Program Research Results

Exploratory Advanced Research . . .  
Next-Generation Transportation Solutions

The EAR Program addresses the need for longer term, higher risk research with the potential for transformative improvements to transportation systems. 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 by experts from different disciplines who have the talent and interest in researching solutions and might 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 toward 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.
- Technology for Assessing Performance.
- New Technology and Advanced Policies for Energy and Resource Conservation.

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#### Cover photos

*Left: DMask—an identity masking system—exchanges the driver's head in naturalistic driving video data with a computer-generated avatar head that preserves key facial landmarks as well as information about head pose, facial expression, and direction of gaze. This gives researchers access to important facial cues while protecting the identity of volunteer drivers (see page 49). © SRI International.*

*Right: Two-dimensional light detection and ranging, or LIDAR, uses satellite-based lasers to provide accurate lane-level information about vehicle positioning in urban driving environments (see page 24). Source: FHWA.*

The results of EAR Program-funded projects may include new fundamental insights about how they can be applied in highway transportation. These projects may lead to new research methods, models, or data that can accelerate applied research or to new system concepts or prototypes, including laboratory testing and, possibly, limited field testing. The EAR 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 11 solicitations, the EAR Program has awarded 88 projects (19 of which are ongoing) involving both government and academic researchers. These projects represent the investment of \$88 million in FHWA funds and leverage \$28 million in matching funds. The following pages contain summary descriptions of the results of selected, recently completed research investigations.

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From an origin in the Department of Agriculture's Office of Public Road Inquiry over 120 years ago, the Federal Highway Administration (FHWA) has been committed to shepherding innovations from ideas to practical applications.

Over the past decade, the FHWA Exploratory Advanced Research (EAR) Program has been the focus of early-stage, higher risk research where government can demonstrate the potential of new ideas for improving the safety, reliability, and state of good repair of the Nation's highways. Examples include the following:

- Early vehicle aerodynamic and traffic modeling and physical testing of technology to control truck spacing in two- and three-truck platoons that showed the potential for reducing fuel use (see pages 14-16).
- The characterization and modeling of new materials that can supplement and substitute the use of portland cement, providing more choices for building and reconstructing the structures and pavements that connect people across the United States (see pages 28-29, 31-32, 34-39).
- The application of experimental economics to daily travel, combined with the development of agent-based models, that can result in improved travel time reliability at a system level (see pages 51-53, 56-57).
- New sensor systems that monitor conditions on and off the roadway, from identifying cracks in structures before they are visible to aiding the movement of wildlife under and over roadways (see pages 64-70).

With rapid change in communications, machine learning, automation, and other technologies, it is increasingly critical to have a program focused on the potential of cutting-edge concepts and how they can provide new opportunities for making travel safer, easier, and more cost effective.

Hari Kalla  
Associate Administrator for Research, Development, and Technology  
Federal Highway Administration



## Connected Highway and Vehicle System Concepts

Research projects in this focus area emphasize longer term needs for reaching critical safety and mobility goals by developing the theory for and assessing the feasibility of systems that leapfrog current technological approaches for linking infrastructure with future vehicle and personal mobility technologies. While people may update mobile devices every 2 years, the average age of private motor vehicles is now over 10 years. Roadway signals, infrastructure sensors, truck trailers, and other elements of the highway system have even longer lifecycles before being replaced. Accordingly, new systems need to work with existing equipment while anticipating future technologies. Connected highway and vehicle system research needs to consider the open nature of transportation, legacy components and processes, and the distributed nature of asset ownership and operations.

**PROJECT:** **Advanced Vehicle Tracking Technologies: Sensing and Monitoring Individual Vehicles in Traffic Flow**

**INSTITUTIONS:** Honeywell Corporation, University of Minnesota, and Time Domain Holdings

**COMPLETED:** 2017

**OBJECTIVE:** To develop a traffic-monitoring system that can recognize and track individual vehicles rather than aggregated vehicle patterns, without relying on vehicle-based technology that provides information about location or movement.

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

**RESOURCE:** Fact sheet at <https://www.fhwa.dot.gov/publications/research/ear/17051/index.cfm>

**RESULTS:** Researchers developed an Advanced Vehicle Tracking System (AVTS) that uses ultrawide band (UWB) radar to identify and track individual vehicles as they move through traffic. The system consists of four-radar units, a tracking computer, software that recognizes vehicle targets, and a user interface display. The four radars in each unit are arranged as rectangles, with each one capable of receiving its own reflected UWB signal and the signals of the other three. The radars in each unit fire sequentially as vehicles pass, transmitting a combined 200 scans/s to a tracking computer and the software, which is called a vehicle recognition engine. The software identifies each vehicle by size, direction, and



## Connected Highway and Vehicle System Concepts

speed as a unique track on the user display, and it shares key information with adjacent radar rectangles as vehicles move through the AVTS. Initial testing showed that the radar units, which are housed in weatherproof enclosures, are most effective when mounted on poles 20 ft high and with an antenna angle of 15 degrees.

**IMPACT:** The AVTS enhances the collection of complex traffic data by focusing on individual vehicles rather than aggregated vehicle patterns, and it does not rely on vehicle-based technology. The UWB radar at the core of the system offers a potential solution to the shortcomings of three other vehicle-sensing technologies—inductive loop detectors, microwave radar sensors, and video imaging systems.



Battery-powered AVTS radar housed in weatherproof case on adjustable-height tower. Source: FHWA.



## Connected Highway and Vehicle System Concepts

**PROJECT:** Using Cooperative Adaptive Cruise Control to Form High-Performance Vehicle Systems

**INSTITUTIONS:** University of California, Berkeley, California Partners for Advanced Transportation Technology; and Technical University of Delft, Netherlands

**COMPLETED:** 2017

**OBJECTIVE:** To overcome the key technical challenges to implementing cooperative adaptive cruise control, clearing the way for field operational tests that will be needed to enable commercialization of the technology.

**CONTACT:** Carl Andersen, FHWA Office of Operations R&D

**RESOURCES:** Fact sheet at <http://www.fhwa.dot.gov/publications/research/ear/16044/index.cfm>

Liu, H., Kan, X., Shladover, S.E., Lu, X.-Y., et al. Modeling Impacts of Cooperative Adaptive Cruise Control on Mixed Traffic Flow in Multi-Lane Freeway Facilities, *Transp. Res. Part C Emerg. Technol.*, 2018, 95: 261-279, at <http://dx.doi.org/10.1016/j.trc.2018.07.027>.

Liu, H., Xiao, L., Kan, X., Shladover, S.E., et al. *Using Cooperative Adaptive Cruise Control (CACC) to Form High-Performance Vehicle Streams. FINAL REPORT*, UC Berkeley: California Partners for Advanced Transportation Technology, 2018, at <https://escholarship.org/uc/item/8pw857gb>.

Kan, X., Liu, H., Shladover, S.E., and Lu, X.-Y. *Using Cooperative Adaptive Cruise Control (CACC) to Form High-Performance Vehicle Streams. Microscopic Traffic Model Calibration and Validation*, UC Berkeley: California Partners for Advanced Transportation Technology, 2018, at <https://escholarship.org/uc/item/5jx899dv>.

**RESULTS:** To bridge gaps in knowledge about cooperative adaptive cruise control (CACC), researchers for this project identified various operational concepts, developed simulation models to test those concepts, and analyzed the results to inform future vehicle experiments. The concepts encompassed multiple strategies for operating CACC platoons. Created with a new program called Microscopic Open Traffic (MOTUS) and the commercially available Aimsun system, the team's



## Connected Highway and Vehicle System Concepts

simulation models represented different real-world road conditions (urban, rural, highways, and arterial) and rates of traffic. Researchers at both the University of California at Berkeley and the Technical University of Delft in the Netherlands used the simulation models to assess how various ways of deploying CACC impacted traffic flow and fuel consumption. The flow assessments included increases achieved in traffic capacity per highway lane, reductions in traffic disturbances, and savings in travel times along arterial roadways. Splitting the simulation tests between the two university teams enabled them to validate each other's work. Researchers also tested their simulation models at FHWA's Saxton Transportation Operations Laboratory in McLean, VA.

**IMPACT:** Researchers used data from this project and two generations of tests at California Partners for Advanced Transportation Technology to verify the feasibility of various CACC strategies. Their work also expanded understanding of how drivers choose to use CACC and clarified the safety implications of the technology. Their simulations advanced efforts to test and evaluate CACC on the road, the next step toward deploying the technology in the real world.



FHWA test vehicles simulate a "platoon" of vehicles using cooperative adaptive cruise control.  
Source: FHWA.



## Connected Highway and Vehicle System Concepts

### Simulations of Connected Vehicle (CV) Technologies

CV technologies that make it possible for vehicles and roadway infrastructure like traffic signals to "talk" to each other can enhance safety, improve mobility, shorten travel time, and reduce the environmental impact of traffic. To achieve those goals, the engineers who are developing CV applications need a reliable, standardized way to test the technologies in various simulated conditions. These software simulations take into account vehicle speed, traffic volume, road conditions, signal timing, and other details at every stage of traffic flow. They also show how a change to any one simulated element affects the other elements in the scenario.

To foster further study of CV technologies, the EAR Program funded two research projects that incorporated actual vehicle performance data into modeling and simulation platforms.

**CONTACT:** **Peter Huang** FHWA Transportation Operations Concepts and Analysis Team

**RESOURCES:** Fact sheet at <https://www.fhwa.dot.gov/publications/research/ear/17044/index.cfm>

Zulkefli, M.A.M., Mukherjee, P., Sun, Z., Zheng, J., et al. Hardware-in-the-Loop Testbed for Evaluating Connected Vehicle Applications, *Transp. Res. Part C Emerg. Technol.*, 2017, 78: 50-62, at <https://doi.org/10.1016/j.trc.2017.02.019>.

Songchitruksa, P., Sunkari, S., Ugalde, I., Rosca, J., et al. Interlinking Vissim and ns-3 for Connected Vehicle Simulation: Case Study of Intelligent Dilemma Zone Avoidance, *TRR, JTRB*, 2018, 2679, at <http://dx.doi.org/10.3141/2679-04>.

**IMPACT:** The insights gained from these in-the-loop simulations will enhance the ability of traffic engineers to accurately and quickly model complex traffic environments. This realistic modeling in turn will foster the development of CV applications and their future deployment in real traffic.



## Connected Highway and Vehicle System Concepts

**PROJECT:** New Approaches for Testing Connected Highway and Vehicle Systems

**INSTITUTIONS:** Texas A&M University Transportation Institute (TTI), Battelle Memorial Institute, and Siemens Corporation

**COMPLETED:** 2017

**OBJECTIVE:** To develop a simulation environment that incorporates data from a connected vehicle and signals in a roadway network into a simulation.

**RESULTS:** Researchers demonstrated a simulation platform called CONnected Vehicle Assessment Simulation (CONVAS) that merges features of the VISSIM traffic simulation software with features of ns-3, an open-source wireless communications simulation. CONVAS integrates data from actual operating roadway elements at a TTI highway test facility and the Connected Vehicle Testbed at the Turner-Fairbank Highway Research Center (TFHRC). Novel “hardware-in-the-loop” features of the platform send this data into a simulation model. CONVAS then shows how real and simulated elements like vehicle speed, traffic volume, road conditions, and signal timing interact in real time. The platform can model interactions for many CV scenarios, including a disruption in the wireless communications that are needed to keep the various elements in the CV environment talking to each other.



CONVAS incorporates data from actual connected vehicles and traffic signals (left) into a simulation that displays the interaction among the vehicles and infrastructure. © Texas A&M Transportation Institute.



## Connected Highway and Vehicle System Concepts

**PROJECT:** Building a Hardware-in-the-Loop Simulation Testbed

**INSTITUTIONS:** University of Michigan and University of Minnesota

**COMPLETED:** 2017

**OBJECTIVE:** To develop a hardware-in-the-loop system that simulates a vehicle engine in the lab for various connected and autonomous vehicles (CAV) operation scenarios and precisely measures the fuel consumption, and to use sophistic measuring devices in the lab.

**RESULTS:** For CV technologies to fulfill their potential, engineers must be able to run simulations that can realistically measure vehicle fuel economy and emissions. Researchers for this project developed a hardware-in-the-loop system that uses a real engine in the lab, which is exactly the same type as the engine used in the CAV at TFHRC, and the traffic simulation software VISSIM to achieve that goal. There are four key parts in the system—a gas engine, a hydrostatic dynamometer, VISSIM, and a laboratory-housed hardware testbed. The dynamometer controls the engine’s load and output to a powertrain model, while the software transmits the road and traffic conditions and the vehicle-specific performance data that researchers select. The data is sent over the Internet to the hardware testbed, which precisely measures actual emissions and fuel consumption. This in-the-loop-simulation system is a simpler and less costly form of analysis than equipping multiple test vehicles with large precision measurement devices.



The in-lab testbed ensures that the engine has the same load as the engine running in the field-test CAV with an onboard unit (OBU) under various operation scenarios. The engine’s emission and fuel consumption are precisely measured by the lab’s powerful devices. Source: FHWA.





## Connected Highway and Vehicle System Concepts

### Truck Platooning and Connectivity

Fuel costs make the movement of freight over long distances an increasingly costly venture. Even small improvements in highway efficiency could reduce the costs per mile significantly, so new technologies and strategies that foster such efficiency would be economically beneficial. One such approach is incorporating CACC into Class 8 tractor-trailers, the kind typically used in freight transportation. CACC consists of radar, global positioning system (GPS) applications, video cameras, and data exchange operating within a dedicated short-range communication (DSRC) system. It allows multivehicle “platoons” of trucks to communicate with each other so they can automatically adjust engine and brake usage to maintain speed and separation distance.

The EAR Program funded two research projects that explored the use of CACC in freight trucks.

**RESOURCES:** Fact sheet at <https://www.fhwa.dot.gov/publications/research/ear/17045/index.cfm>

Bevly, D., Murray, C., Lim, A., Turochy, R., et al. *Heavy Truck Cooperative Adaptive Cruise Control: Evaluation, Testing, and Stakeholder Engagement for Near Term Deployment: Phase One Final Report*, FHWA, Washington, DC, 2015, at [http://eng.auburn.edu/~dmbevly/FHWA\\_AU\\_TRUCK\\_EAR/FHWA\\_AuburnDATP\\_Phase1FinalReport](http://eng.auburn.edu/~dmbevly/FHWA_AU_TRUCK_EAR/FHWA_AuburnDATP_Phase1FinalReport).

Bevly, D., Murray, C., Lim, A., Turochy, R., et al. *Heavy Truck Cooperative Adaptive Cruise Control: Evaluation, Testing, and Stakeholder Engagement for Near Term Deployment: Phase Two Final Report*, FHWA, Washington, DC, 2017, at [http://eng.auburn.edu/~dmbevly/FHWA\\_AU\\_TRUCK\\_EAR/FHWA\\_AuburnDATP\\_Phase2FinalReport](http://eng.auburn.edu/~dmbevly/FHWA_AU_TRUCK_EAR/FHWA_AuburnDATP_Phase2FinalReport).

Yang, S., Shladover, S.E., Lu, X.-Y., Spring, J., et al. *A First Investigation of Truck Drivers' On-the-Road Experience Using Cooperative Adaptive Cruise Control*, UC Berkeley: California Partners for Advanced Transportation Technology, 2018, at <https://escholarship.org/uc/item/92359572>.



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Ramezani, H., Shladover, S.E., Lu, X.-Y., and Altan, O.D. Micro-Simulation of Truck Platooning with Cooperative Adaptive Cruise Control: Model Development and a Case Study, *TRR, JTRB*, 2018, at <http://dx.doi.org/10.1177/0361198118793257>.

Bishop, R., Bevly, D., Humphreys, L., Boyd, S., et al. Evaluation and Testing of Driver-Assistive Truck Platooning: Phase 2 Final Results. *TRR, JTRB*, 2018, 2615(1): 11-18, at <http://dx.doi.org/10.3141/2615-02>.

**IMPACT:** By using platooning algorithms with CACC devices for these two projects, researchers demonstrated fuel savings at highway speeds. They also concluded that CACC could improve traffic flow once deployment of the technology achieves sufficient market penetration in freight trucks. In addition to cutting fuel costs, this greater efficiency could curtail emissions and reduce the workload for both drivers and vehicles. It would enhance the adaptive cruise control currently available in many tractor-trailers.

**PROJECT:** Heavy Truck Cooperative Adaptive Cruise Control

**INSTITUTIONS:** Auburn University, American Transportation Research Institute, Meritor, Inc., Peloton Technology, and Peterbilt Truck

**COMPLETED:** 2019

**OBJECTIVE:** To quantify the system performance of CACC in a two-truck platoon and evaluate the potential fuel savings that could be achieved by implementing the technology.

**CONTACT:** Kevin Dopart, FHWA Intelligent Transportation Systems Joint Program Office

**RESULTS:** This team's research analyzed the business case, vehicle aerodynamics, and traffic modeling for CACC-equipped truck platoons by conducting on-road tests with two-truck platoons at the Transportation Research Center, Inc., track in Ohio. With CACC controlling the distance between the two trucks, the research showed peak fuel savings of 5 percent for the lead truck, 10 percent for the trailing truck,



CACC incorporates video cameras, a DSRC system for inter-vehicle data exchange, and GPS. © n.d. Auburn University, College of Engineering.



## Connected Highway and Vehicle System Concepts

and 7 percent at peak for the platoon. When the trailing truck stayed 50 ft behind the lead truck (a more realistic distance based on surveys that assessed driver comfort), the trailing truck saved more than 10 percent in fuel. Fleets that average more than 500 mi per trip would yield the highest return on investment in CACC. Researchers found that private and large, over-the-roadline truck fleets would most likely adopt CACC first. Market penetration in truck platoons would need to reach 60 percent to improve overall traffic flow along specific routes.

**PROJECT:** Partial Automation for Truck Platooning

**INSTITUTIONS:** University of California, Berkeley, Partners for Advanced Transportation Technology, Cambridge Systematics, and Volvo Technologies of America

**COMPLETED:** 2018

**OBJECTIVE:** To develop and implement the technology for a three-truck platooning system using vehicle-to-vehicle communications and radar/vision-based sensors.

**CONTACT:** Osman Altan, FHWA Office of Operations R&D

**RESULTS:** University of California, Berkeley researchers tested CACC in three-truck platoons that were operated in real California highway traffic. The driver of the lead truck operated it either manually or with partially automated adaptive cruise control, while the two trailing trucks featured fully automated CACC. Signals from a DSRC system operated at 5.9 GHz synchronized the platoon using a “constant time gap” strategy that separated the trucks proportionally based on their actual speed. The technology made it possible for the third truck to “see” the lead truck and for the platoon to respond in near-zero time to maintain the specified gaps between trucks. In addition to testing how the trucks in the platoon interacted with each other, researchers gauged how they responded to other vehicles changing lanes and getting between two trucks in the platoon. When that happened, the system automatically designated a new lead vehicle for the platoon, and it adjusted the following gap and strategy.



Three Class 8 trucks equipped with CACC during field test. © University of California, Berkeley.



## Connected Highway and Vehicle System Concepts

### Assistive Technologies for Visually Impaired Persons

For roughly 2 million American adults with impaired vision, independent travel and active interactions with the surrounding environment present significant daily challenges. The EAR Program funded three research projects to examine new technology to:

- Help visually impaired persons identify important objects, movements, and text information in the environment.
- Develop solutions to help visually impaired people find their way through indoor and outdoor environments.
- Extend navigation guidance for visually impaired travelers in areas where global positioning system (GPS) data is not reliable.

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

**COMPLETED:** 2016

**RESOURCES:** Details at [http://www.its.dot.gov/research\\_archives/attri/index.htm](http://www.its.dot.gov/research_archives/attri/index.htm)

Tian, L., Yi, C., and Tian, Y. Detecting Good Quality Frames in Videos from Mobile Camera for Blind Navigation, *J. Computer Vision Image Processing*, October 2015, 5(10).

Pierce, J.D., Bevely, D.M. *A Centralized Approach to Pedestrian Localization Using Multiple Odometry Sources*, Proc. of the 2015 International Technical Meeting of The Institute of Navigation, Dana Point, CA, January 2015.

**IMPACT:** Together, these three research projects will provide new methods for visually impaired and other people with disabilities to maneuver through dynamic environments. Ultimately, the advances made in this research will provide fundamental benefits for travelers on foot, on a bicycle, driving a motorcycle or car, or operating a commercial vehicle.

**PROJECT:** Intelligent Situation Awareness and Navigation Aid for Visually Impaired Persons

**INSTITUTION:** City College of the City University of New York

**OBJECTIVE:** To develop technologies that detect and track stationary and moving objects, read signs, and monitor movement to support wayfinding and navigation of visually impaired people through indoor and outdoor environments.



## Connected Highway and Vehicle System Concepts

**RESULTS:** Researchers for this project focused on exploring and developing awareness and navigation technologies that can recognize stationary objects; read and recognize important text and signage; and detect, track, and represent moving objects and other dynamic changes. The system includes a wearable device with integrated sensors, such as cameras, three-dimensional orientation sensors and pedometers, and a unit that will provide auditory and tactile guidance. Ultimately, this system will provide the user with a navigation map, register landmarks on the map, and generate a verbal description or tactile feedback for blind users to obtain a global perception of their environment.



Researchers demonstrate the Intelligent Situation Awareness Navigation Aid at U.S. Department of Transportation headquarters. Source: FHWA.

**PROJECT:** Navigation Guidance for People with Vision Impairment

**INSTITUTION:** TRX Systems, Inc.

**OBJECTIVE:** To develop navigational technologies that will localize, track, and plan a route for visually impaired users anywhere, including areas without access to GPS information.

**RESULTS:** Key elements of this research include developing a navigational aid that can localize and track the location of a blind person anywhere, including indoors or in urban areas where GPS data is not available or not reliable; plan and adaptively update a route that allows a visually impaired person to get to a destination; provide guidance through tactile information instead of relying solely on auditory instructions; use computer vision techniques to find stairs, elevators, hallways, and doors to help with navigation; and verify that the user has reached the correct destination.



The navigation aid developed by TRX Systems, Inc.  
© TRX Systems, Inc.



## Connected Highway and Vehicle System Concepts

**PROJECT:** Extended Event Horizon Navigation and Wayfinding for Blind and Visually Impaired Pedestrians in Unstructured Environments

**INSTITUTION:** Auburn University

**OBJECTIVE:** To develop a navigation system that can fill the gaps where GPS data is not sufficient and present information to visually impaired users when it is needed, whether they are indoors or outdoors.

**RESULTS:** Researchers for this project demonstrated the utility of a specialized pedestrian navigation device that integrates GPS, inertial measurement units, visual odometry, and stored and updated map data to accurately capture the movements of a pedestrian user in environments such as parks, airports, intersections, and general pedestrian zones. Where GPS is not available, the inertial measurement and odometry units can continue to provide accurate positioning and navigation information. The device communicates with the user through a system that combines vibration and tactile sensations with an iPhone app to indicate path and navigation information.



A chest-mounted stereo camera and inertial measurement unit form part of Auburn University's pedestrian navigation system.  
© Auburn University.

**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 <https://www.fhwa.dot.gov/research/tfhrc/projects/projectsdb/projectdetails.cfm?projectid=FHWA-PROJ-07-0026>

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



## Connected Highway and Vehicle System Concepts

**RESULTS:** The project team 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.

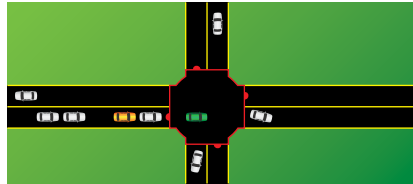
**IMPACT:** As automated vehicles come onto the market, results from this project have the potential to provide a safe system for improving traffic flow and dramatically reducing fuel use and mobile-source emissions at intersections.

**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; and 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.



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. Source: FHWA.

## Connected Highway and Vehicle System Concepts

**CONTACT:** Peter Huang, FHWA Office of 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 [https://www.ocf.berkeley.edu/~xuanvg/doc/Argote\\_Christofa\\_Xuan\\_Skabardonis\\_2012\\_TRB.pdf](https://www.ocf.berkeley.edu/~xuanvg/doc/Argote_Christofa_Xuan_Skabardonis_2012_TRB.pdf)

Fact sheet at <https://www.fhwa.dot.gov/publications/research/ear/11044/11044.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.



Traffic crossing an intersection. © www.istockphoto.com.

**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

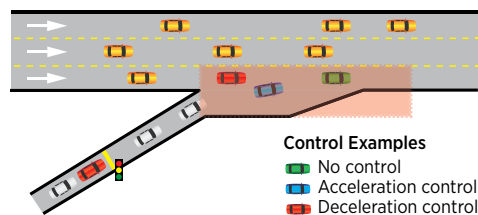
**OBJECTIVE:** To develop and evaluate candidate freeway merge-assistance systems that might improve the efficiency and safety of freeway merges in a connected vehicle environment.

**CONTACT:** Carl Andersen, 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). Source: FHWA.



## 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, and Stanford Research Institute

**COMPLETED:** 2012

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

**CONTACT:** Mohammed Yousuf, 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 <https://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 Light Detection and Ranging (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. Source: FHWA.

**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

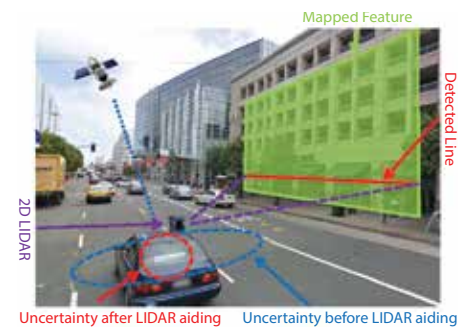
**OBJECTIVE:** To investigate and test a range of approaches that could provide lane-level positioning accuracy in diverse driving environments.

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

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

**RESULTS:** No single positioning technology can meet the requirements for lane-level positioning across diverse driving environments—each has performance limitations. Researchers for this project explored the most promising technologies for improving the accuracy, availability, and reliability of vehicle positioning by augmenting Global Navigation Satellite System/INS technology. After evaluating the performance of aiding technologies (Light Detection and Ranging (LIDAR), radar, computer vision, and 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. Source: FHWA.



## Connected Highway and Vehicle System Concepts

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

**INSTITUTIONS:** Ohio State University, University of Virginia, and GNSS 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.

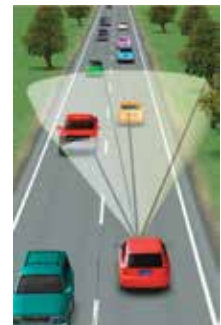
**CONTACT:** Mohammed Yousuf, FHWA Office of Operations R&D

**RESOURCES:** Fact sheet at <https://www.fhwa.dot.gov/publications/research/ear/13065/13065.pdf>

*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 3.9 inch 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 reduced 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.



CarSim is a vehicle simulator utilized by Ohio State University to develop realistic vehicle trajectories. © Mechanical Simulation Corporation.





## Connected Highway and Vehicle System Concepts

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

**INSTITUTIONS:** California PATH, University of California, Berkeley; and 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:** Carl Andersen, FHWA Office of Operations R&D

**RESOURCES:** Liu, H., Kan, X., Shladover, S.E., and Ferlis, R. Impact of Cooperative Adaptive Cruise Control on Multilane Freeway Merge Capacity, *J. Intell. Transport. Sys.*, 2018, 22(3).

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)

**RESULTS:** The project team modeled, tested, and demonstrated prototype wireless communication systems to improve traffic flow by calculating and communicating variable speed limits (VSLs) to drivers; achieve higher effective lane capacities using 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 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 and 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 <https://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 30 mi/h and distances up to 115 ft away under good visibility conditions and up to 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. Source: FHWA.



## Breakthrough Concepts in Materials Science

Advances in instrumentation allow for measuring materials used to construct the U.S. highway system at time and length scales previously unknown, and they are leading to new insights into fundamental knowledge. Combined with new methods for multiscale material modeling, research in this focus area has the potential for giving the highway industry more choice and increased reliability of materials for highway structures and pavements.

**PROJECT:** **Novel Alternative Cementitious Materials for Development of the Next Generation of Sustainable Transportation Infrastructure**

**INSTITUTIONS:** Georgia Institute of Technology, Oklahoma State University, Tourney Consulting Group, and U.S. Army Corps of Engineers

**TO BE COMPLETED:** 2019

**OBJECTIVE:** To increase access to alternative cementitious materials (ACMs) as potential replacements for ordinary portland cement (OPC) to achieve significant sustainability improvements and to take advantage of the special setting and durability properties of ACMs.

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

**RESOURCES:** Fact sheet at <https://www.fhwa.dot.gov/publications/research/ear/18031/>

Techbrief at <https://www.fhwa.dot.gov/publications/research/ear/16017/index.cfm>

Project details at <https://highways.dot.gov/novel-organic-cementitious-materials-development-next-generation-sustainable-transportation>

**RESULTS:** Researchers for this three-phase project studied various ACMs as potential substitutes for OPC to extend the life of concrete in pavement and bridges. The researchers reviewed relevant literature, visited sites to evaluate the long-term performance of ACMs, and interviewed producers and users of the materials before conducting their own tests of ACMs. Using OPC as a control measure, the researchers first looked at nine ACMs—three calcium sulfoaluminate (CSA), one polymer-modified CSA, two calcium aluminate (CA), one portland/CA/calcium sulfate ternary blend, one chemically activated Class C fly ash (AA1), and one magnesium



## Breakthrough Concepts in Materials Science

phosphate (MP) binder. For the second phase of work, they narrowed the focus to two CSA cements, two CA cements, and AA1 based on the promise they showed for use in transportation infrastructure. Tests of those five ACMs within concrete gauged their ability to resist physical abrasion, progressive alkali silica reactivity deterioration, and other threats. Phase 3 of the project featured more corrosion tests, extended lab testing, long-term field exposure studies, and forensic analysis of well-aged ACM-based pavements.



Concrete slump made of an alternative cementitious material (calcium sulfoaluminate). © College of Engineering, Georgia Institute of Technology.

**IMPACT:** ACMs expand the options available to designers, owners, and contractors of concrete-based transportation

infrastructure. They require less energy to create than portland cement and generate less carbon dioxide, resulting in significant sustainability improvements, and they may be particularly valuable in concrete exposed to extreme environments. This research provides insights that can be used to recommend test methods for ACMs and preliminary specifications for their use.

**PROJECT:** **Novel Development of Bio-Based Binder for Sustainable Construction**

**INSTITUTIONS:** Washington State University and Pavement Preservation Systems

**COMPLETED:** 2018

**OBJECTIVE:** To produce a bio-based substance that is comparable or superior in performance to petroleum-based asphalt binders for use in constructing roads and other similar projects.

**CONTACT:** **Jack Youtcheff**, FHWA Office of Infrastructure R&D

## Breakthrough Concepts in Materials Science

**RESOURCE:** Project details at <https://highways.dot.gov/novel-development-bio-based-binder-sustainable-construction>

**RESULTS:** Researchers for this project mixed waste cooking oil with lignin, a byproduct of the paper pulping process, to create a bio-based asphalt binder. To develop the binder, the researchers first mixed the waste cooking oil with maleic anhydride at 365°F and used iodine as a catalyst. This initiated a chemical reaction in the oil to boost its molecular weight, a process known as polymerization. Next, the team put the lignin through chemical processes to create an epoxy. Because it is more stable at high temperatures, the lignin-derived epoxy makes roads built with the bio-based asphalt binder more resistant to rutting, well-worn depressions, and grooves. Researchers then preblended the polymerized waste cooking oil and lignin, and they mixed that substance with asphalt aggregates in a hot drum to create a “bioasphalt.” After curing the mixture for 2 hours, they packed the bioasphalt in a gyratory compactor. The goal of the research was to create a substance that provides as much or more resistance to fatigue, rutting, thermal cracking, and moisture as petroleum-based asphalt.

**IMPACT:** Successfully producing a bio-based asphalt binder that equals or exceeds the performance of traditional asphalt could reduce the reliance on petrochemicals in road networks. The results of this project could contribute to future research into bioasphalt, including its ability to withstand various traffic loads and weather conditions based on the degrees of the binder’s polymerization.



Researchers created a rotary reactor to simulate the production of the hot-mix bio-binder through mixing aggregates with bioasphalt. © 2017 Department of Civil and Environmental Engineering, Washington State University.

## Breakthrough Concepts in Materials Science

**PROJECT:** **Mechanisms of Hydration and Setting of Ordinary Portland Cement in Simple and Complex Systems**

**INSTITUTIONS:** Princeton University; National Institute of Standards and Technology (NIST); Oklahoma State University; Rice University; University of California, Santa Barbara; and W.R. Grace and Company

**COMPLETED:** 2017

**OBJECTIVE:** To develop advanced hydration models that will improve the setting, strength, and durability of concrete and provide guidance on a pavement’s expected performance based on the composition of cement, supplementary cementitious materials, admixtures, and temperature.

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

**RESOURCES:** Fact sheet at <https://www.fhwa.dot.gov/publications/research/ear/15084/index.cfm>

Fonseca, P.C., and Scherer, G.W. An Image Analysis Procedure to Quantify the Air Void System of Mortar and Concrete, *Mater. Struct.*, 2015, 48(10), 3087-3098.

Stoian, J., Oey, T., Bullard, J.W., Huang, J., et al. New Insights into the Prehydration of Cement and its Mitigation, *Cem. Concr. Res.*, 2015, 70, 94-103.

Li, X., Grasley, Z.C., Bullard, J.W., and Garboczi, E.J. Computing the Time Evolution of the Apparent Viscoelastic/Viscoplastic Poisson’s Ratio of Hydrating Cement Paste, *Cem. Concr. Compos.*, 2015, 56, 121-133.

Bullard, J.W., Scherer, G.W., and Thomas, J.J. Time Dependent Driving Forces and the Kinetics of Tricalcium Silicate Hydration, *Cem. Concr. Res.*, 2015, 74, 26-34.

Sangodkar, R.P., Smith, B.J., Gajan, D., Rossini, A.J., et al. Influences of Dilute Organic Adsorbates on the Hydration of Low-Surface-Area Silicates, *J. Am. Chem. Soc.*, 2015, 137, 8096-8112.





## Breakthrough Concepts in Materials Science

Hu, Q., Aboustait, M., Kim, T., Ley, M.T., et al. Direct Three-Dimensional Observation of the Microstructure and Chemistry of  $C_3S$  Hydration, *Cem. Concr. Res.*, 2016, 88, 157-169, at <http://dx.doi.org/10.1016/j.cemconres.2016.07.006>.

Bullard, J.W., and Scherer, G.W. Solid Solution Model for C-S-H, *J. Am. Ceram. Soc.*, 2016, 99(12), 4137-4145.

Hu, Q., Aboustait, M., Kim, T., Ley, M.T., et al. Direct Measurements of 3D Structure, Chemistry and Mass Density during the Induction Period of  $C_3S$  Hydration, *Cem. Concr. Res.*, 2016, 89, 14-26, at <http://dx.doi.org/10.1016/j.cemconres.2016.07.008>.

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Bellmann, R., and Scherer, G.W. Analysis of C-S-H Growth Rates in Supersaturated Conditions, *Cem. Concr. Res.*, 2018, 103, 236-244, at <http://dx.doi.org/10.1016/j.cemconres.2017.05.007>.

**RESULTS:** Researchers combined experimental measurement techniques with computer modeling to observe, measure, and model the hydration process in cement at scale. The team conducted the research in two phases, with the first focused on the mechanisms of cement hydration and the second on the impact of organic admixtures. The researchers used experimental techniques like vertical scanning interferometry, tomography-assisted chemical correlation, and nuclear magnetic resonance spectroscopy to identify mechanisms to include in their models. Using these techniques, the researchers obtained data to verify model predictions and validate models at nano-, micro-, and macroscopic length scales. They also discovered breakthrough techniques that allowed them to obtain even more information about reaction rates. The studies enabled them to identify which chemical reactions occur at the early ages of cement, where



Researchers conducted x-ray nano-computed tomography and nano-x-ray fluorescent imaging using the Beamline 26 x-ray nanoprobe at Argonne National Laboratory in Illinois. © Argonne National Laboratory, managed and operated by UChicago Argonne, LLC, for the U.S. Department of Energy.



## Breakthrough Concepts in Materials Science

they occur within the cement, at what rate, and how they can be modified to make concrete more sustainable and durable. These insights will help improve the hydration reaction simulation and modeling programs being developed at NIST and other institutions. The data has resulted in published technical papers that have helped refine the modeling efforts being advanced at NIST, including the hydration reactions in a microstructures project (<https://www.nist.gov/programs-projects/hydration-reactions-microstructures-project>) and the Virtual Cement and Concrete Testing Laboratory software (<https://www.nist.gov/services-resources/software/vcctl-software>).

**IMPACT:** By creating a tool to observe cement at its material length scales, this project helped advance the control of hydration in cement. Researchers applied their knowledge from the project toward improving NIST's HydratiCA model for simulating hydration and toward developing SimBNG, a boundary nucleation and growth model. FHWA will make the research available by technique, mineral, additive, and other key words for future experimentation.

**PROJECT:** **Nanoscale Approaches for Inhibiting Corrosion: Green Advanced Coatings for Application on Steel Structures and Bridges**

**INSTITUTION:** City College of New York

**COMPLETED:** 2018

**OBJECTIVE:** To slow the deterioration of steel infrastructure with safer, corrosion-resistant coatings, and to develop a model to help bridge owners set optimal rehabilitation schedules for steel bridges.

**CONTACT:** Jack Youtcheff, FHWA Office of Infrastructure R&D

**RESOURCES:** Fact sheet at <https://www.fhwa.dot.gov/publications/research/ear/13064/index.cfm>

Project details at <https://highways.dot.gov/nanoscale-approaches-inhibiting-corrosion-green-advanced-coatings-application-steel-structures-and>

**RESULTS:** High maintenance and rehabilitation costs are the motivation for research into new types of steel coatings that inhibit corrosion, resist scratching, and reduce environmental risk. This particular project focused on creating a nanotechnology-based coating that meets those requirements at a lower lifecycle cost while also being easy to apply, fast to dry, and resistant to ultraviolet rays. The first phase of work incorporated nanomaterials into two



## Breakthrough Concepts in Materials Science

novel coating systems—a polyaniline (PANI) epoxy system with added carbon black and a nanoclay-enhanced calcium sulfonate alkyd (CSA) system. Researchers compared different concentrations of these coatings with zinc-rich epoxy primer coatings, which have been common since the 1960s. The PANI-epoxy system performed better than the nanoclay-enhanced CSA system in corrosion tests, but the latter material had stronger adhesion, dried more quickly, and was more resistant to scratching. Phase 2 encompassed tests of two alternative additives for the CSA-based system, accelerated testing and weathering studies of the PANI and CSA systems, and a 16-month study of the PANI system and the CSA system that performed best.

**IMPACT:** Nano-enhanced, corrosion-resistant, and environmentally friendly coatings for steel could help extend bridge service life and keep the driving public safe. By providing insights into the use of nanomaterials in steel coatings, this project advanced lifecycle management of steel bridges. Data from the research was used to estimate lifetime deterioration of structural components. The research results could have applications for many steel structures besides bridges.

**PROJECT:** **Inorganic Polymers: Novel Ordinary Portland Cement-Free Binders for Transportation Infrastructure**

**INSTITUTIONS:** University of California, Los Angeles; University of California, Santa Barbara; University of Texas, Austin; and Boral Materials

**COMPLETED:** 2018

**OBJECTIVE:** To determine how inorganic polymer binders made from fly ash react with certain chemical solutions and improve understanding of how those reactions affect binder performance and production.

**CONTACT:** **Jack Youtcheff**, FHWA Office of Infrastructure R&D

**RESOURCES:** Gomez-Zamorano, L., Balonis, M., Erdemli, B., Neithalath, N., et al. C-(N)-S-H and N-A-S-H Gels: Compositions and Solubility Data at 25 c and 50 c, *J. Am. Ceram. Soc.*, 2017, 100(6): 2700-2711.

Kumar, A., Oey, T., Falzone, G., Huang, et al. The Filler Effect: The Influence of Filler Content and Type on the Hydration Rate of Tricalcium Silicate, *J. Am. Ceram. Soc.*, 2017, 100(7): 3316-3328.



## Breakthrough Concepts in Materials Science

Oey, T., Kumar, A., Pignatelli, I., Yu, Y., et al. Topological Controls on the Dissolution Kinetics of Glassy Aluminosilicates, *J. Am. Ceram. Soc.*, 2017, 100(12): 5521-5527.

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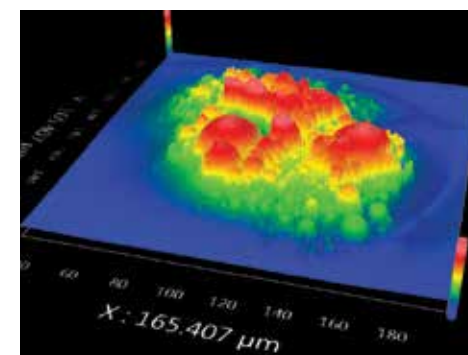
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Oey, T., Kumar, A., Falzone, G., Huang, J., et al. The Influence of Water Activity on the Hydration Rate of Tricalcium Silicate, *J. Am. Ceram. Soc.*, 2016, 99(7): 2481-2492.

Pignatelli, I., Kumar, A., Bauchy, M., and Sant, G. Topological Control on Silicates' Dissolution Kinetics, *Langmuir*, 2016, 32(18): 4434-4439.

**RESULTS:** Various researchers are striving to develop concrete that uses less energy in its manufacture and costs less. This team focused its efforts on “cement-free” inorganic polymer binders (IPBs) that could “glue” the raw materials in concrete together. They examined fly ash, a byproduct from coal-fired power plants, as a potential alternative to ordinary portland cement,



A three-dimensional image acquired using vertical scanning interferometry that shows a cluster of fly ash particles. © Henry Samueli School of Engineering and Applied Science, University of California, Los Angeles.



## Breakthrough Concepts in Materials Science

the traditional binder in concrete. To study how fly ash reacts when introduced into certain chemical solutions, researchers developed a molecular design strategy. First, they analyzed the compositional and physical parameters of fly ash to identify the desired characteristics for producing IPBs. Next, the team used solid- and liquid-phase nuclear magnetic resonance, vertical scanning interferometry, and molecular simulations to examine at the atomic scale the molecular processes and products that result when cement-free binders react under typical conditions. Among other insights, researchers learned how chemical species formed in the solutions. In the last phase of research, the team used an embedded material properties database to study the evolution of IPBs throughout a reaction.

**IMPACT:** This project contributed to the understanding of how cement-free binders made from fly ash may perform in highway infrastructure. Researchers developed tools and methodologies that could improve the ability to manufacture IPBs and help the construction industry integrate industrial byproducts into building materials.

**PROJECT:** **Paving the Way for Greener Highways: Extending Concrete's Service Life through Multiscale Crack Control**

**INSTITUTION:** University of California, Berkeley

**COMPLETED:** 2015

**OBJECTIVE:** To extend the service life of reinforced concrete structures by limiting the spread of cracks, and to reduce the environmental impact of concrete by incorporating recycled waste materials.

**CONTACT:** **Terry Arnold**, FHWA Office of Infrastructure R&D

**RESOURCES:** Fact sheet at <https://www.fhwa.dot.gov/publications/research/ear/13079/13079.pdf>

Details at <http://www.asce.org/engineering-mechanics/emi-research-profiles/durability-mechanics-at-the-university-of-california-berkeley/>

**RESULTS:** The research team demonstrated the effectiveness, environmental benefit, and cost savings of an approach called deterioration reduction through micro and macro crack control (DRMC) that significantly slows the deterioration



## Breakthrough Concepts in Materials Science

of highways, bridges, and other major concrete structures, while reducing the environmental costs of concrete construction.

The first component of the DRMC research—hybrid fiber-reinforced concrete (HyFRC)—evaluated the use of a mix of water-soluble polymer microfibers (0.312 inch) and hooked-end steel macro fibers (1.170 inch) to limit the development and spread of cracks, which reduce concrete's strength and speed up its deterioration. Compared with conventional concrete, HyFRC showed significant improvement in corrosion control, due mainly to suppression of spreading cracks. The second component of DRMC tested a “green” variant of HyFRC that uses fly ash—a waste product of burning coal to generate electricity—to replace 50 percent of the portland cement in concrete. In addition, the green HyFRC uses recycled concrete aggregate, which is commonly sent to landfills, to replace natural stone and gravel used in concrete. Tests showed that the green DRMC approach achieved both goals—enhanced corrosion resistance and conservation of natural resources.

**IMPACT:** Achieving significant crack and corrosion resistance in concrete that incorporates recycled waste material represents an economical and effective next-generation approach to major infrastructure construction projects, with increased service life expectancy and reduced environmental impact.



Two concrete samples using equivalently reactive aggregate. Left, ASR-damaged concrete with cracks marked; right, crack-resistant HyFRC for concrete strength and stiffness retention. © 2013 Claudia Ostertag.





## Breakthrough Concepts in Materials 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, and 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 [https://www.nrmca.org/research\\_engineering/Documents/Lab\\_fly\\_ashFinal\\_report.pdf](https://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 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.



Fly ash with different carbon content levels. Source: FHWA.



## Breakthrough Concepts in Materials Science

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

**INSTITUTION:** 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:** Fact sheet at <https://www.fhwa.dot.gov/publications/research/ear/09065.pdf>

Technical report at <http://d2dtl5nnlpr0r.cloudfront.net/swutctamu.edu/publications/technicalreports/476660-00017-1.pdf>

Research article at <http://www.hindawi.com/journals/inm/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.



Carbon nanofibers spanning nano/micro crack in a cementitious composite. Source: FHWA.



## Human Behavior and Travel Choices

New mobile sensors and computers are creating radical new tools for understanding how individuals and groups of people behave, both in structured experiments and in natural, everyday life. With advances in automation, there also are new demands for understanding how people interact with machines. The EAR Program has supported research in this focus area on mining data to create new methods of assessing long-distance passenger travel, freight data, and safety surrogate measures. The EAR Program also is taking advantage of advances in machine learning to increase the automated coding of naturalistic driving data. Demonstrating novel approaches for harnessing the advances in enabling technologies can result in more effective safety countermeasures, roadway designs, and system investments that can better reflect the future needs of people and goods to travel.

### Knowledge Discovery in Massive Transportation Datasets

The ability to extract and analyze safety-related information from vast datasets about driver behavior, vehicle performance, traffic patterns, weather, and infrastructure could help reduce crashes on the Nation's highways. These datasets include FHWA's Highway Safety Information System (HSIS), which features data on accident, roadway, and traffic variables; the naturalistic driving study (NDS), a resource from the second Strategic Highway Research Program (SHRP 2) that describes more than 3,400 drivers and vehicles involved in roughly 36,000 events; and a related SHRP 2 Roadway Information Database (RID), which details NDS trips on the most frequently traveled roadway sections. Open-source technology that can process these massive transportation datasets is needed to enhance knowledge discovery.

The EAR Program backed two projects designed to develop such technology.

**CONTACTS:** Ana Maria Eigen and James Pol, FHWA Office of Safety R&D

**RESOURCES:** Hankey, J.M., Perez, M.A., and McClafferty, J.A. *Description of the SHRP 2 Naturalistic Database and the Crash, Near-Crash, and Baseline Data Sets*, Task Report Prepared for the Strategic Highway Research Program 2, Transportation Research Board of the National Academies, April 2016, at <https://vtechworks.lib.vt.edu/handle/10919/70850>.

For Palo Alto Research Center, Inc. (PARC) projects, see "PARC-projects" on GitHub, at <https://github.com/PARC-projects/video-query-home>.



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**IMPACT:** The first project will enable researchers to leverage decades of information in existing transportation datasets, work with data sources not typically considered in the safety domain, and broaden their understanding of safety countermeasures. The platform the researchers developed also could have applications in operations and maintenance if the necessary datasets are added to it. Tools developed through the second project will be refined for use with similar data-rich traffic information resources.

**PROJECT:** Applications of Knowledge Discovery in Massive Transportation Data: The Development of a Transportation Research Informatics Platform (TRIP)

**INSTITUTION:** CUBRC

**COMPLETED:** 2018

**OBJECTIVE:** To manage massive amounts of transportation data and provide researchers an efficient way to conduct analytics on "Big Data."

**RESULTS:** Researchers at CUBRC developed a tool called the Transportation Research Informatics Platform (TRIP). Built on a LINUX operating system, TRIP features open-source tools that ingest, transform, align, and store massive amounts of traffic data that users can mine for patterns related to traffic safety. The platform's versatile dashboard makes it possible to visualize streaming data and historical information. This includes State road crashes, traffic volumes, and roadway characteristics from the HSIS; roadway geometrics from the RID; data on historical crashes, traffic volumes, weather, traffic laws, safety campaigns, and work zones; weather data and roadway surface conditions from the Clarus Initiative; and weather information like precipitation, temperature, and wind speed from the Iowa Environmental Mesonet. CUBRC tested TRIP with sample datasets from the Seattle region.



An illustration of the study area being examined in TRIP, including 4,277 mi of centerline data and 27 roadway weather information stations. © 2017 CUBRC.



## Human Behavior and Travel Choices

**PROJECT:** **High Performance Data Fusion for Transportation Safety Analytics**

**INSTITUTION:** Palo Alto Research Center, Inc.

**COMPLETED:** 2018

**OBJECTIVE:** To combine and analyze data from large datasets in the transportation domain, including datasets containing sensitive personal and business information.

**RESULTS:** Researchers at the Palo Alto Research Center, Inc. (PARC) developed automated, machine-learning methods to extract, clean, and restructure traffic-related data from disparate sources. They used video, radar, and still photography information gathered from Chicago intersections. This new approach, an improvement upon slower, manual methods for handling such data, can reveal safety issues that might not be apparent from examining traditional datasets. When the SHRP 2 NDS became available, PARC started developing a video analysis tool. Being tested now, this tool processes snippets of video and can return the location on the video matching the snippet.



Interactive feedback on the examples proposed by PARC's automated machine-learning method for agile video queries. © Palo Alto Research Center, Inc.

### Video Analytics Research Projects

The Naturalistic Driving Study (NDS) conducted by the second Strategic Highway Research Program (SHRP 2) of the Transportation Research Board collected 1.2 million hours of video from more than 3,400 volunteer drivers and their vehicles traveling on U.S. highways over a period of 2 years. This is one of the largest and richest resources for transportation safety researchers. Each vehicle was equipped with an interface to collect data from the vehicle's on-board systems, video cameras, GPS, and other systems that combined to generate more than 2 petabytes of data.

The EAR Program funded six separate research projects that addressed separate aspects of video analytics, with the common goal of helping



## Human Behavior and Travel Choices

researchers manage and extract accurate information from the large and complex SHRP 2 data set.

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

- RESOURCES:** Baragchizadeh, A., Karnowski, T.P., Bolme, D.S., and O'Toole, A.J. *Evaluation of Automated Identity Masking Method (AIM) in Naturalistic Driving Study (NDS)*, 2017 12th IEEE International Conf. on Automatic Face & Gesture Recognition (FG 2017), Washington, DC, May 30-June 3, 2017, 378-385.
- Paone, J., Bolme, D., Ferrell, R., Aykac, D., et al. *Baseline Face Detection, Head Pose Estimation, and Coarse Direction Detection for Facial Data in the SHRP2 Naturalistic Driving Study*, 2015 IEEE Intelligent Vehicles Symposium (IV), Seoul, South Korea, June 28-July 1, 2015, 174-179.
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- Zeng, J., Chu, W-S., de la Torre, F., and Xiong, Z. Confidence Preserving Machine for Facial Action Unit Detection, *IEEE Trans. Image Process.*, 2016, 25(10):1-1.
- Seshadri, K., and Savvides, M. Towards a Unified Framework for Pose, Expression, and Occlusion Tolerant Automatic Facial Alignment, *IEEE Trans. Pattern Anal. Machine Intell.*, 2015, 38(10).
- Radwin, R.G., Lee, J.D., and Akkas, O. *Are Driver Movement Patterns Indicators of Distraction and Engagement?* Proc. Human Factors





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and Ergonomics Society 59th Annual Mtg., University of Wisconsin-Madison, 2015.

Schwarz, C., Brown, T., Lee, J., Gaspar, J., et al. *The Detection of Visual Distraction Using Vehicle and Driver-Based Sensors*, SAE Technical Paper, 2016, 01-0114.

Seshadri, K., Juefei-Xu, F., Pal, D., Savvides, M., et al. *Driver Cell Phone Usage Detection on Strategic Highway Research Program (SHRP2) Face View Videos*, IEEE Conf. on Computer Vision and Pattern Recognition, 2015, 35-43.

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

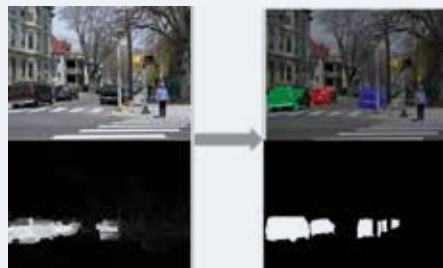
**INSTITUTION:** Carnegie Mellon University

**COMPLETED:** 2016

**OBJECTIVE:** To develop a prototype tool that uses computer vision and machine-learning algorithms to identify and extract useful information about roadway features from data gathered from forward-looking, vehicle-mounted cameras.

**RESULTS:** Researchers evaluated analytical solutions to challenges such as identifying multiple roadway features (car and truck detection), differentiating among scene context elements (vegetation, sky, and roadway shoulder), and identifying traffic signs and status of traffic signals. The researchers also developed a simple graphical user interface that enables even novice users to effectively employ appropriate algorithms to a range of analytical tasks.

**IMPACT:** This research demonstrates the effectiveness of applying appropriate machine-learning techniques to large, diverse data sets and opens avenues for active learning to address challenges such as traffic congestion control, driver behavior training, and road safety.



A typical challenging situation for overlapping objects (left vehicles) and occluded objects (right vehicle) in an urban environment. © Carnegie Mellon University.



## Human Behavior and Travel Choices

### Automated Feature Extraction Projects

The EAR Program sponsored three research projects designed to advance efficient and cost-effective methods and tools to analyze the large amounts of video-related safety data generated by studies such as the SHRP 2 NDS. These projects focused on the driver and the interior of vehicles involved. Each project brings different technical strengths and approaches and applies the approaches to different features of interest for highway safety. These projects are briefly summarized below.

**PROJECT:** DCode: A Comprehensive, Automated Coding System for Driver Behavior Analysis

**INSTITUTION:** SRI International

**COMPLETED:** 2016

**OBJECTIVE:** To develop a comprehensive, automatic system to assist in coding of features in the SHRP 2 NDS data set that are relevant to traffic and roadway safety researchers.

**RESULTS:** Researchers for this project developed software to code contextual features such as passengers, radio, navigation, and conditions outside the vehicle. The software extracts core and intermediate features to code driver behavior features (e.g., hand position and facial expression) and to track driver attention (emotional, cognitive, and physiological state). The project identified areas for future research, such as image stabilization and improved techniques to extract contextual features when the environment is not ideal, such as when seat belts are not brightly colored and difficult to detect.

**IMPACT:** This project demonstrates the effectiveness of a coding system that makes it possible to identify and evaluate the actions and behaviors of drivers, as well as the context in which they are performed.



The DCode System will extract driver behavior features and recognize various actions. It will also track contextual features. © SRI International.

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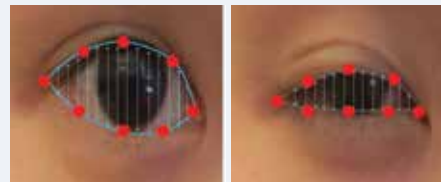
### **PROJECT:** DB-SAM: CMU Driver Situational Awareness System

**INSTITUTION:** Carnegie Mellon University

**COMPLETED:** 2016

**OBJECTIVE:** To develop an automated, real-time method for analyzing key facial landmarks to determine if a driver is fatigued or distracted.

**RESULTS:** DB-SAM uses Active Appearance Models to analyze facial images and Active Shape Models to analyze facial outlines by tracking a variety of physical and biological landmarks in videos. This analysis is used to estimate driver distraction or fatigue. Researchers also evaluated



Examples of how the distance between the curves of the eyelids could be used for eye openness classification. © Carnegie Mellon University.

methods to analyze hand position to determine if drivers have their hands on the steering wheel or are holding a cell phone to their ear.

**IMPACT:** This project demonstrates the potential for using real-time video analytics to estimate if a driver is in good condition to operate a vehicle.

### **PROJECT:** Quantifying Driver Distraction and Engagement Using Video Analytics

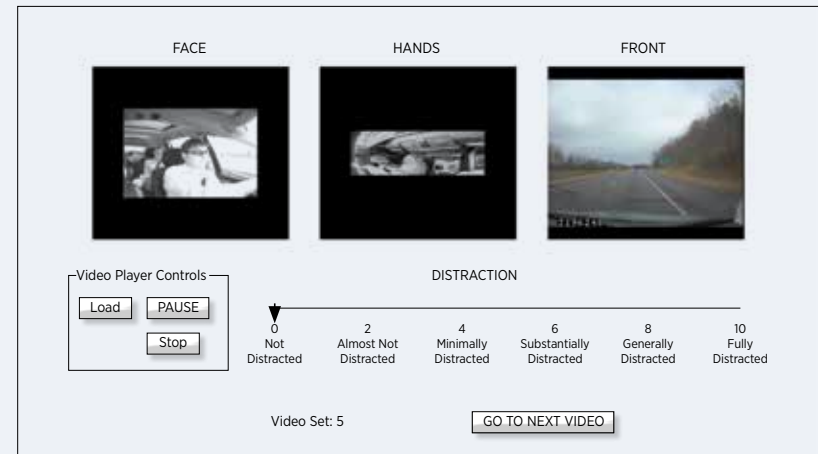
**INSTITUTION:** University of Wisconsin-Madison

**COMPLETED:** 2016

**OBJECTIVE:** To develop an open software system and graphical user interface that will enable automated feature extraction and behavior characterization using naturalistic driving video.

**RESULTS:** This research team evaluated automated feature extraction and behavior characterization systems to estimate driver distraction and engagement, as well as road state. In this system, algorithms segment video into regions of interest that include the driver's head, face, and upper body; steering wheel; and roadway. The software tracks facial landmarks to estimate head pose, tracks eye and mouth movement to help estimate gaze, and monitors hand activity to determine if a driver's hands are on the steering wheel. The software also

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Regions of interest, including the driver's face, hands, and front view, are monitored by the system. © Regents of the University of Wisconsin-Madison.

evaluates features of road state (e.g., traffic signal detection, day or night, in traffic or alone on the road). This information is used to help understand driver engagement.

**IMPACT:** This research represents an important advance toward development of a reliable, automated, video coding system that can be used with naturalistic or driving-simulator video to help understand and prevent driver distraction.

### **Automated Identity-Masking Projects**

The EAR Program supported two research projects designed to investigate automated identity masking that preserves underlying information about the driver's expression (e.g., head pose, mouth, and eye movement) while protecting privacy and precluding personal identification. The following pages provide a brief summary of these two projects.

### **PROJECT:** Automation of Video Feature Extraction for Road Safety—Automated Identity-Masking

**INSTITUTIONS:** Carnegie Mellon University and University of Pittsburgh

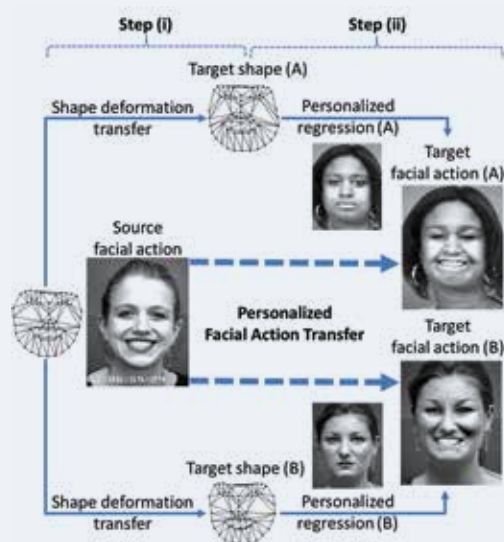
**COMPLETED:** 2016

**OBJECTIVE:** To develop an automated, facial-masking technique to prevent personal identification without eliminating facial behavior.



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**RESULTS:** The research team for this project developed automated masking techniques that protect personal identity while allowing future researchers to analyze facial behavior as a tool to help evaluate driving characteristics through study of naturalistic driving videos. The central concept employed in this research is facial action transfer, which clones a facial action (e.g., forming a smile) from one person within a video to another person. This process preserves the changing subtle facial movements from the person being de-identified. The process is nonreversible, ensuring that driver identity is protected. Researchers have developed an automatic graphical user interface that can output de-identified video.



The personalized facial action transfer process.  
Chart: © Carnegie Mellon. Face images: © University of Pittsburgh.

**IMPACT:** This project demonstrates the effectiveness of an automated system for de-identifying individuals in naturalistic driving videos, greatly expanding the utility of these videos in driver safety and behavior studies.



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**PROJECT:** **DMask: A Reliable, Identity-Masking System for Driver Safety Video Data**

**INSTITUTION:** SRI International

**COMPLETED:** 2016

**OBJECTIVE:** To develop an automated facial-masking technique to prevent personal identification without eliminating distinctive aspects of driver expression.

**RESULTS:** This research involved exchanging the driver's head in SHRP 2 video data with a computer-generated avatar head. The system preserves key facial landmarks as well as information about head pose, facial expression, direction of gaze, and the state of the eyes and mouth. This information about facial motion is automatically and accurately mapped to the avatar face, giving researchers access to important facial cues while protecting individual identity. A manual-assist feature allows users to manually correct mis-mapping of the eyes, nose, and mouth.

**IMPACT:** This project helps broaden the research value of data collected in naturalistic driving videos, by retaining often subtle but relevant facial movements while protecting the identity of volunteer drivers.



A driver's identity is protected using an avatar to replace their face in all frames. ©SRI International.





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**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=F-HWA-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.



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**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 R&D

**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 project will help researchers understand future travel demands, improve transportation system management and travel reliability, and provide valuable investment insight for maintaining urban transport systems and services in the Washington, DC—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.

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

**INSTITUTIONS:** University of Arizona and 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:** **James Pol**, FHWA Office of Safety R&D

**RESOURCES:** Fact sheet at <https://www.fhwa.dot.gov/publications/research/ear/12069/12069.pdf>

Project details at <http://www.fhwa.dot.gov/research/tfhrc/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 team delivered a set of comprehensive modeling tools and a revolutionary system for a multi-agent modeling system

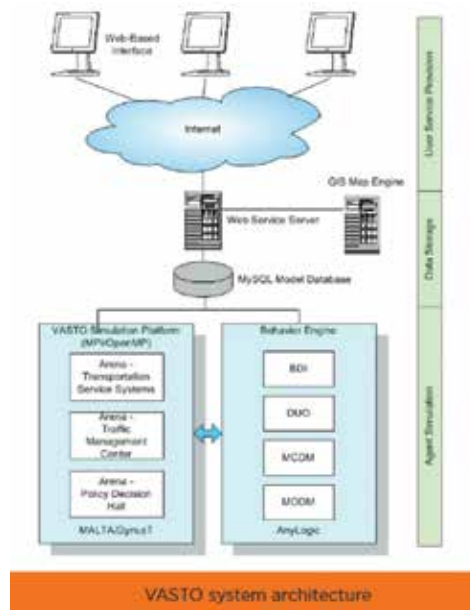


Image credit: Yi-Chang Chiu, Ph.D.

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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 decisionmaking on transportation investments and contribute to effective management strategies, leading to a safer, more efficient transportation system.

**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 SHRP 2's 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



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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.

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

**INSTITUTIONS:** Batelle, The Urban Institute, and 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

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

**RESULTS:** Researchers for this 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 had 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



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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.

**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.; and 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



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





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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.

**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.

**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 Bureau of Transportation Statistics

**RESOURCES:** Study fact sheet 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



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choices to test whether their behavior could predict field driver behavior. The study concluded 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.

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

**INSTITUTIONS:** University of Michigan and 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:** **Carl Andersen**, 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 of a rail transit station and worked within 3 mi 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



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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.

**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

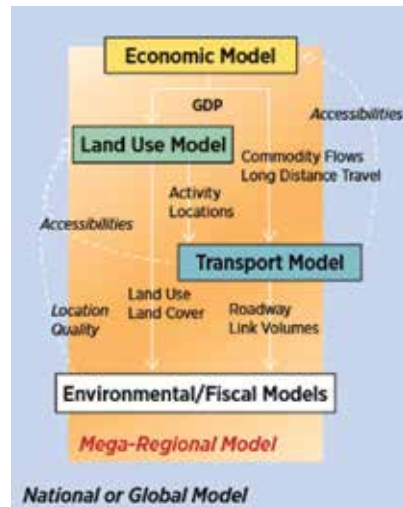
**OBJECTIVE:** To develop methods and tools that support planning for the Nation's megaregions, integrating multiple disciplines, travel modes, and geographic levels.

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

**RESOURCES:** Fact sheet at <https://www.fhwa.dot.gov/publications/research/ear/12024/12024.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



The model components recommended for megaregion analysis. © University of Maryland.



## Human Behavior and Travel Choices

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 policymakers 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.

**PROJECT:** Driver Behavior in Traffic

**INSTITUTIONS:** Virginia Polytechnic Institute and State University, PTV America, and 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:** James Pol, FHWA Office of Safety R&D

**RESOURCES:** Fact sheet at <https://www.fhwa.dot.gov/publications/research/ear/10070/10070.pdf>

Final reports 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



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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.



Example of a sudden lane change. © Rorem, Dreamstime.com.

**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.



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**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, and 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, and Realty

**RESOURCE:** Project website 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 and 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



Advances in science and technology are providing new approaches in signal processing and data management. Sensors are continuing to increase in number, with many becoming disposable or recyclable and being embedded in almost everything sold. Advances in energy scavenging, batteries, and efficient spectrum use can increase in orders of magnitude the amount of processing that can take place at the source and the amount that can be transmitted for post hoc analysis. At the same time, computational models are becoming more complex and realistic, providing even more data than captured in the physical world. The EAR Program is supporting research in this focus area that demonstrates the potential of new approaches that can support transportation decisionmakers in finding meaning among increasing noise—from determining where damage is occurring on structures before it is visible to inspectors to improving the quality of new construction through intelligent compaction.

**PROJECT:** Self-Sensing Adaptive Material for a New Generation of Multifunctional Bridge-Bearing Systems

**INSTITUTION:** University of Nevada, Reno

**COMPLETED:** 2017

**OBJECTIVE:** To develop self-sensing adaptive bridge bearing systems capable of sensing and redistributing traffic- or environmental loads.

**CONTACT:** Sheila Duwadi, FHWA Office of Infrastructure R&D

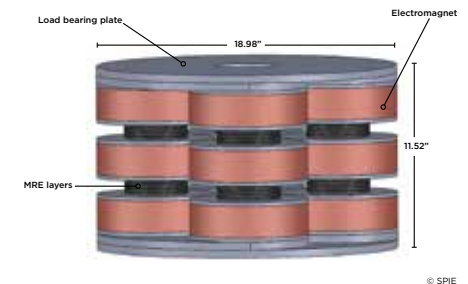
**RESOURCE:** Fact sheet at <https://www.fhwa.dot.gov/publications/research/ear/17046/index.cfm>

**RESULTS:** Part of a three-phase study to identify material composition and develop systems responsive to loadings experienced by bridges, this research examined the value of magnetorheological elastomers (MREs) as a smart material for self-sensing adaptive bridge bearings (SSABs). MREs are polymeric solids embedded with iron particles. Their beneficial characteristics include piezoresistivity and magnetoresistance; the incorporation of MREs into SSABs makes it possible to measure structural loading continually and transmit that information to a monitoring system. The first two phases of research involved a series of groundbreaking investigations that demonstrated the feasibility of using MREs in highway bridge isolation bearings. Through a methodological design process, the bearings were developed to accommodate large strain and

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force demands. Experimental evaluations during these two phases showed that adaptive features of the bearings in terms of real-time control of apparent shear stiffness were attainable. However, further investigation was deemed necessary to develop material compositions to realize higher magnetorheological (MR) effects. The third phase focused on furthering MRE materials development under large strains to improve the MR effects. It characterized the mechanical properties of silicone-based and natural rubber-based MREs to improve MR effects under large strains.



Bearings composed of MRE material sandwiched between electromagnet arrays adjust stiffness and dampening properties in response to strain. © 2016 Proc. SPIE.

**IMPACT:** The vibrations caused by wind and traffic are a significant factor in bridge performance, and conventional passive bearings, because of their predetermined stiffness, are limited in their ability to suppress such vibrations and readjust. This research showed that MREs incorporated within SSABs add stability to adaptive mechanical properties while withstanding realistic forces. The electrical properties of the layers also can be adjusted to measure changes in electrical resistance and correlate that to bearing forces.

**PROJECT:** Cooperating Camera Platforms for Ultra-High-Resolution Traffic Surveillance and Autonomous Event Detection

**INSTITUTION:** University of Maryland

**COMPLETED:** 2015

**OBJECTIVE:** To provide continuous, high-resolution, real-time simultaneous monitoring, tracking, and analysis of multiple transportation events or characteristics.

**CONTACT:** Taylor Lochrane, FHWA Office of Operations R&D

**RESOURCE:** Fact sheet at <https://www.fhwa.dot.gov/publications/research/ear/15068/index.cfm>

**RESULTS:** The cameras that traditionally monitor transportation incidents, infrastructure, and congestion often require human monitoring and produce

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low-resolution video. Researchers for this project developed a high-resolution system that can monitor and analyze multiple incidents or characteristics at once and in real time. The cameras are synchronized, and their pan, tilt, and zoom features enhance the detection of any issues in the highway network. The cameras “talk” to each other every 50 milliseconds about what they are seeing so the system as a whole can track potentially fast-moving vehicles. The reach of the high-resolution imagery for highway infrastructure is up to 5 mi. The precisely calibrated camera lenses and high-performance gimbals also provide accurate video of vehicles at long distances. The system transmits footage wirelessly to remote operation centers and to other network locations at up to 1 gigabit/s, as traffic events dictate. The team designed and developed a testbed at the University of Maryland campus and on a local state highway.



Real-time video feature extraction (top), and cameras that can cooperate using precise and fast electronic pan, tilt, and zoom gimbals for event detection (bottom).  
© University of Maryland.

**IMPACT:** The camera system developed in this project offers great promise for improved monitoring of transportation infrastructure. It will enhance the quality of the video feeds, the speed in which they are delivered to observers, and the perspectives and information they provide. The high-bandwidth communications network will make it possible for personnel in an operations center to immediately detect events and for emergency responders in the field to get situational updates instantaneously. The testbed at the University of Maryland can be used for subsequent research into high-resolution traffic cameras.

**PROJECT:** Remote, Wireless Camera Systems for Environmental Monitoring of Transportation Corridors

**INSTITUTION:** University of California, Davis’ Road Ecology Center

**COMPLETED:** 2017

**OBJECTIVE:** To develop wireless wildlife camera technology that advances the state of the practice in investigating wildlife movement near highways, and to create an online interface and database to manage images from camera traps.

## Technology for Assessing Performance



**CONTACT:** Deirdre Remley, FHWA Office of Project Development and Environmental Review

**RESOURCES:** Fact sheet at <http://www.fhwa.dot.gov/publications/research/ear/16033/index.cfm>

Shilling, F. *Using Advanced Camera Systems for Environmental Monitoring of Transportation Corridors* (webinar #1’s slides). University of California, Davis, Road Ecology Center, Wildlife Observer Network, January 31, 2017, at [https://wildlifeobserver.net/files/resources/WEBINAR\\_Jan31\\_ppt.pdf](https://wildlifeobserver.net/files/resources/WEBINAR_Jan31_ppt.pdf).

Shilling, F. *Using Advanced Camera Systems for Environmental Monitoring of Transportation Corridors* (webinar #2’s slides). University of California, Davis, Road Ecology Center, Wildlife Observer Network, February 8, 2017, at [https://wildlifeobserver.net/files/resources/WEBINAR\\_Feb8\\_ppt.pdf](https://wildlifeobserver.net/files/resources/WEBINAR_Feb8_ppt.pdf).

Shilling, F. *Using Advanced Camera Systems for Environmental Monitoring of Transportation Corridors* (webinar #2’s recording and slides). University of California, Davis, Road Ecology Center, Wildlife Observer Network, February 8, 2017, at <https://wildlifeobserver.net/content/advanced-camera-systems-webinar-recording-slides-audio>.

Questions and Answers from Both Advanced Camera Systems Webinars. University of California, Davis, Road Ecology Center, Wildlife Observer Network, n.d., at [https://wildlifeobserver.net/files/resources/ChatboxQuestions\\_Answers\\_Webinars1\\_2\\_0.pdf](https://wildlifeobserver.net/files/resources/ChatboxQuestions_Answers_Webinars1_2_0.pdf).



Wildlife cameras operated in coordination with the California Department of Transportation captured images of two deer (left) and a bear (right) safely using wildlife crossings under Interstate 680 and under Interstate 80, respectively. © U.C. Davis Road Ecology Center.



## Technology for Assessing Performance

**RESULTS:** The researchers demonstrated the potential for creating affordable, accessible remote camera systems for transportation agencies to continuously monitor and study wildlife movements in traffic corridors. The approach they developed can use commercially available wildlife cameras that have wireless or cellular connections to servers, and can be incorporated into existing traffic camera infrastructure. Using a Web interface, the system receives image files directly from remote wireless cameras, or transportation agency personnel can upload batches of images manually. Uploaded images are automatically organized into a database using details like date and time, geographic location, and user information. Users can manually add animal type, gender, age, observed activity, direction traveled, and any other characteristics to each image file. In the next and current phase of the project, researchers are exploring the use of software to automatically flag images with no animals and identify common wildlife species. State transportation agencies can use the Wildlife Observer Network, available at <https://wildlifeobserver.net>, to collect, manage, analyze, and share images. The website includes training materials and webinars produced by the research team. Agencies in California, Colorado, South Dakota, and Utah helped field test the system.

**IMPACT:** FHWA and seven other Federal agencies will use the technology developed for this project as part of a broader plan to promote ecosystem-based environmental mitigation by integrating plans and data across agencies. The innovations will help agencies acquire wildlife movement data more easily and safely and at less cost than deploying staff periodically to collect images from static wildlife cameras mounted near highways.

### Assessing the Structural Health of America's Highway Bridges: Effective Wireless Sensor Systems to Monitor Structural Health and Detect Damage

The ability to monitor the condition of bridges and other civil infrastructure systems is of primary interest to all infrastructure owners and operators. The development of advanced structural monitoring methods can facilitate the early detection of possible structural damage deterioration, with the goal to extend the lifespan of structures and increase their safety. Timely information gathered from such technologies undoubtedly will help transportation agencies in the corrective and urgent decisionmaking process. The



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development of wireless networks has eliminated the need for performing the arduous task of stringing connecting cables.

The EAR Program supported two research projects—battery-powered wireless sensors and wireless sensors that operate without batteries—aimed at developing cost-effective structure health monitoring.

**CONTACT:** Fred Faridazar, FHWA Office of Infrastructure R&D

**RESOURCES:** Fact sheet at <https://www.fhwa.dot.gov/publications/research/ear/17043/index.cfm>

Hasni, H., Lajnef, N., Alavi, A.H., Aono, K., et al. *Local-Global Damage Identification Approach Using Hybrid Network of Self-Powered Sensors*, The 7th World Conference on Structural Control and Monitoring, Qingdao, China, July 22-25, 2018.

Hasni, H., Jiao, P., Alavi, A.H., Lajnef, N., et al. *Structural Health Monitoring of Steel Frames Using a Network of Self-Powered Strain and Acceleration Sensors: A Numerical Study*, *Automat. Constr.*, 2018, 85, 344-357.

Aono, K., Hasni, H., Pochettino, O., Lajnef, N., et al. *Quasi-Self-Powered Infrastructural Internet of Things: The Mackinac Bridge Case Study*, Proc. of the 2018 Association for Computing Machinery's (ACM) Great Lakes Symposium on Very Large Scale Integration (VLSI), Chicago, IL, May 23-25, 2018.

Alavi, A.H., Hasni, H., Jiao, P., Borchani, W., et al. *Fatigue Cracking Detection in Steel Bridge Girders through a Self-Powered Sensing Concept*, *J. Constr. Steel Res.*, 2017, 128, 19-38.

Hasni, H., Alavi, A.H., Jiao, P., and Lajnef, N. *Detection of Fatigue Cracking in Steel Bridge Girders: A Support Vector Machine Approach*, *Arch. Civ. Mech. Eng.*, 2017, 17(3), 609-622.

Hasni, H., Alavi, A.H., Lajnef, N., Abdelbarr, M., et al. *Self-Powered Piezo-Floating-Gate Sensors for Health Monitoring of Steel Plates*, *Eng. Struct.*, 2017, 148, 584-601.

Hasni, H., Jiao, P., Alavi, A.H., and Lajnef, N. *Damage Localization and Quantification in Gusset Plates: A Battery-Free Sensing Approach*, *Struct. Control. Hlth.*, 2017.



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Hasni, H., Alavi, A.H., Jiao, P., and Lajnef, N. *A New Method for Detection of Fatigue Cracking in Steel Bridge Girders Using Self-Powered Wireless Sensors*, SPIE Smart Structures and Materials + Nondestructive Evaluation and Health Monitoring, International Society for Optics and Photonics, 2017, 101680Q-101680Q.

Alavi, A.H., Hasni, H., Jiao, P., and Lajnef, N. *Structural Health Monitoring Using a Hybrid Network of Self-Powered Accelerometer and Strain Sensors*, SPIE Smart Structures and Materials + Nondestructive Evaluation and Health Monitoring, International Society for Optics and Photonics, 2017, 101682N-101682N.

Furkan, M., Mao, Q., Mazzotti, M., DeVitis, J., et al. *An Investigation on Wireless Sensors for Asset Management and Health Monitoring of Civil Structures*, Proc. SPIE, Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems, 2016, 9803.

Furkan, M.O., Mao, Q., Livadiotis, S., Mazzotti, M., et al. *Multipurpose Wireless Sensors for Asset Management and Health Monitoring of Bridges*, Structural Health Monitoring of Intelligent Infrastructure Conference, Brisbane, Australia, 2017.

Furkan, M.O., Mao, Q., Livadiotis, S., Young, C., et al. *Field Validation of Multipurpose Wireless Sensors for Bridge Assessment*, NDE/NDT Structural Materials Technology for Highways and Bridges (SMT) and the International Symposium on Non-Destructive Testing in Civil Engineering (NDT-CE), New Brunswick, NJ, 2018.

**IMPACT:** The wireless sensor systems that researchers developed can efficiently collect and transmit data to bridge owners so they can monitor structural health and compare conditions against reliable baseline data on an ongoing basis. The ability to deploy the systems and collect measurements rapidly will enhance bridge testing and condition assessments.

**PROJECT:** Ultra Low-Power Wireless Sensing System

**INSTITUTIONS:** Michigan State University, Washington University in St. Louis, and the University of Southern California

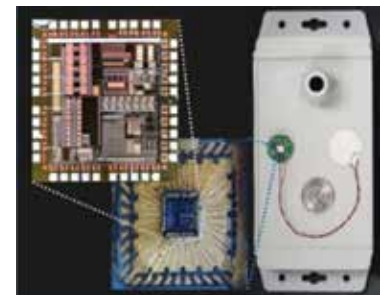
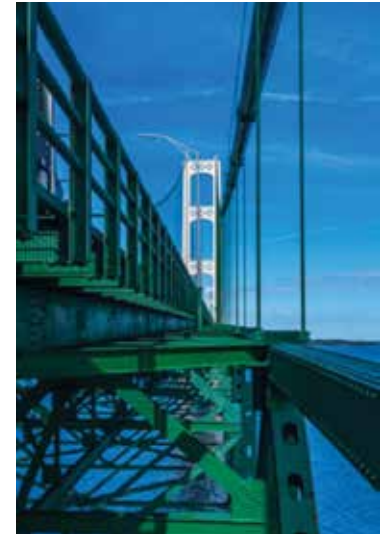
## Technology for Assessing Performance



**COMPLETED:** 2018

**OBJECTIVES:** To advance the practical application of structural health monitoring methodologies for bridges by developing self-powered sensor technology, and to investigate novel damage prognosis methods and effective sensor implementation strategies.

**RESULTS:** This team of researchers explored the benefits of self-powered piezoelectric-floating-gate (PFG) sensors. These materials are capable of converting mechanical energy, such as strains and vibrations, into electrical energy. The generated electrical signals, which are directly proportional to the mechanical excitation, also are used to power all electronics in the sensing system. The researchers' models integrated finite element, experimental testing, and statistical and artificial intelligence. The information delivered by the piezoelectric transducer is stored in these gates. The gates record the duration of strain/voltage events when the amplitudes of the input signals, generated by the piezoelectric transducer, exceed certain predetermined thresholds. The output of the sensor is presented in the form of a histogram, in which each gate denotes the cumulative time of the events at a specific, predetermined strain level. Prototypes of the PFG sensor and telemetry box were deployed on the Mackinac Bridge for fatigue-prone monitoring of structure components.



Top to bottom: Michigan's Mackinac Bridge and a 0.468-inch piezoelectric transducer. © Michigan State University.

## Technology for Assessing Performance

**PROJECT:** Multipurpose Wireless Sensors for Asset Management and Health Monitoring of Structures

**INSTITUTIONS:** Drexel University and Smartsensys

**COMPLETED:** 2018

**OBJECTIVES:** To transform reliable wired sensors, including displacement sensors, strain gauges, and accelerometers, into wireless devices to allow rapid bridge structural assessments.

**RESULTS:** The battery-powered wireless sensors developed in this project eliminated the need for long cables to connect sensors to data loggers, a process that is costly and time-consuming. The wireless sensors can be deployed rapidly, and they establish baseline measurements when bridges are constructed. These measurements can be used later to assess potential bridge damage from floods, accidents, and other incidents. Field tests of the technology accurately measured factors like strain, displacement, and tilt of structural components. One field test on a multispan bridge that has experienced significant vibration showed that wireless strain and displacement gauges are as accurate as wired sensors. A second field test on a multispan steel bridge over the Delaware River used wireless accelerometers to extract and study vibration properties (mode shapes and frequencies) and calibrate a numerical model of the structure.



The sensors pictured in the inset image—wireless magnetic strain gauge (left), wireless displacement gauge (middle), and wireless accelerometer (right)—were tested on this 11-span viaduct carrying Interstate 76 west of Philadelphia, PA. © Drexel University.

## Technology for Assessing Performance

**PROJECT:** A Remote, Self-Sustained System for Monitoring Water Quality Near Highways

**INSTITUTION:** Montana State University

**COMPLETED:** 2015

**OBJECTIVE:** To develop an in situ water monitoring system that can provide real-time data and is powered by fuel cells that use biological activity of common stream bacteria to generate electricity.

**CONTACT:** Damaris Santiago, FHWA Office of Project Development and Environmental Review

**RESOURCES:** Fact sheet at <https://www.fhwa.dot.gov/publications/research/ear/16018/index.cfm>

Project summary at <https://www.fhwa.dot.gov/advancedresearch/pubs/16018/16018.pdf>

More information at [https://www.environment.fhwa.dot.gov/ecosystems/wet\\_storm.asp](https://www.environment.fhwa.dot.gov/ecosystems/wet_storm.asp)

**RESULTS:** Collecting water quality data from streams near highways can be difficult in hard-to-reach or remote locations. Conventional sample collection and laboratory analysis miss important information about pollution that occurs over short periods, such as highway spills or in the first flush of stormwater runoff from highways. In this project, researchers demonstrated the feasibility of using microbial fuel cells (MFC) as a reliable power source for onsite sampling instruments. The MFCs



The project's control system collects, processes, and transmits the real-time water quality data provided by the in situ sensors. © Qing Yang, Montana State University.

## Technology for Assessing Performance



harvest power from electrochemical reactions driven by naturally occurring bacteria that oxidize magnesium, which is common in stream water. The MFCs generate electricity during periods of high biological activity and act as batteries to store and release energy as needed during periods of low biological activity. The system's sensor array uses wireless open-source (TelosB) sensors attached to probes that provide information on water quality measures, including temperature, dissolved oxygen, chloride concentration, and pH. Because energy generation by the MFCs fluctuates, researchers also developed a power management system that can release stable voltage over short periods to power in situ sensors. A 3-month field test in a natural stream showed that the system can provide continuous monitoring of key water quality measures at a frequency of four to seven samples per day.

**IMPACT:** This project represents an important advance toward the goal of developing a network of real-time, self-powered, environmental monitoring stations that will reduce manpower and logistical costs while improving the reliability and accuracy of monitoring to protect and maintain water quality near highways.

**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:** Yi, X., Cho, C., Cooper, J., Wang, Y., et al. Passive Wireless Antenna Sensor for Strain and Crack Sensing—Electromagnetic Modeling, Simulation, and Testing, *Smart Materials Struct.*, 2013, 22, 085009, at <http://iopscience.iop.org/0964-1726/22/8/085009/>.

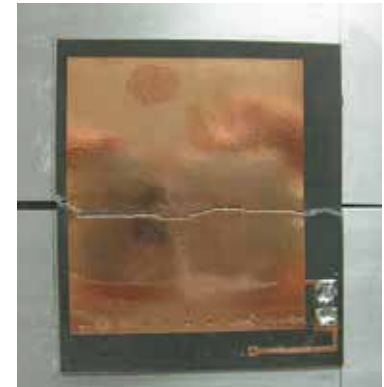
Yi, X., Wu, T., Wang, Y., Leon, R.T., et al. Passive Wireless Smart-Skin Sensor Using RFID-based Folded Patch Antennas, *Int. J. Smart Nano Materials*, 2011, 2, 22–38, at <http://www.tandfonline.com/doi/full/10.1080/19475411.2010.545450>.

## Technology for Assessing Performance



Project details at <https://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.  
Source: FHWA.

**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

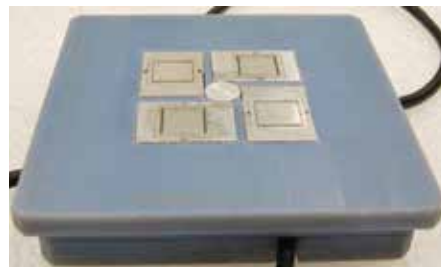
**OBJECTIVE:** To advance technology for measuring and understanding the complex flow fields and boundary shear stresses and pressure fields associated with bridge pier scour.

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

**RESOURCE:** Technical report at <https://ntrs.nasa.gov/search.jsp?R=20120007389>

**RESULTS:** In this project, Jet Propulsion Laboratory investigators 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/s. 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 predominant 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. Source: FHWA.

## 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:** Mooney, M.A. and Rinehart, R.V. Field Monitoring of Roller Vibration during Compaction of Subgrade Soil, *J. Geotech. & Geoenv. Engineering*, ASCE, 2007, 133(2), 257-265.

Rinehart, R.V. and Mooney, M.A. Instrumentation of a Roller Compactor to Monitor Vibration Behavior during Earthwork Compaction, *J. Automation in Construction*, 2008, 17(2), 144-150.

**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 gauges, 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. Source: FHWA.



## New Technology and Advanced Policies for Energy and Resource Conservation

Advances in harvesting and embedding energy are allowing for placement of sensors and control technology where it previously would have been impractical and for increased reliability where current systems are subject to disruption from extreme events. Research in this area combined with new approaches to sensing, assessment, and control will allow for improved resilience of the highway system.

**PROJECT:** **Creating Productive Roadways: Developing an Advanced Energy Production, Storage, and Distribution System**

**INSTITUTION:** University of Nebraska-Lincoln

**COMPLETED:** 2014

**OBJECTIVE:** To use existing roadway and right-of-way infrastructure to produce, store, and distribute stable and renewable electric power.

**CONTACT:** **Eric Weaver**, FHWA Office of Infrastructure R&D

**RESOURCES:** Zhao, M., and Sharma, A. Optimal Deployment of Hybrid Alternative Power System at Signalized Intersections, *TRR, JTRB*, 2015, 2438, 72-80.

Zhao, M., Sharma, A., Bernt, D.G., Meyer, A.J., et al. Economic Analysis of Using Renewable Wind Power System at a Signalized Intersection, *J. Intell. Transport. Sys.: Technology, Planning, and Operations*, Special issue: Intelligent Transportation Systems Applications for the Environment and Energy Conservation (Part 2), 2013, 17(3), 210-220.

Zeng, J., Zhang, Z., and Qiao, W. An Interconnection and Damping Assignment Passivity-Based Controller for a DC-DC Boost Converter with a Constant Power Load, *IEEE Trans. Industry Apps.*, 2014, 50(4), 2314-2322.

Zeng, J., Wei, Q., Qu, L., and Jiao, Y. An Isolated Multiport DC-DC Converter for Simultaneous Power Management of Multiple Different Renewable Energy Sources, *IEEE J. Emerg. Select. Topics Power Electron.*, 2014, 2(1), 70-78.

Zeng, J., and Qiao, W. Short-Term Solar Power Prediction Using a Support Vector Machine, *Renewable Energy*, 2013, 52, 118-127.

## New Technology and Advanced Policies for Energy and Resource Conservation

Zeng, J., and Qiao, W. Short-Term Wind Power Prediction Using a Wavelet Support Vector Machine, *IEEE Trans. Sustain. Energy*, 2012, 3(2), 255-264.

Project information is located at <http://energyplusroadways.unl.edu/info.php?section=overview>

More information at <http://energyplusroadways.unl.edu/>

**RESULTS:** The project investigators demonstrated the feasibility and effectiveness of a Roadway Wind/Solar Hybrid Power Generation and Distribution System (RHPS). Reliable, renewable power generation within the roadway and right-of-way infrastructure can significantly reduce the cost of operating and maintaining highway systems. Excess power generation can be a source of revenue to further offset operating costs. Moreover, reliable and renewable power can provide important backup to keep critical roadway safety and control systems operating during periods of local or regional power failure. The main element of the RHPS is the energy-plus roadway traffic signal light (EPRTL), which includes a wind and solar power system installed on a traffic pole. Key components of the RHPS are:

- Wind turbines and solar panels mounted on the poles of existing traffic signals and street lights.
- High-efficiency, low-cost, electronic power converters, controls, and communication boards.
- Power management algorithms and software to coordinate operation of various EPRTL elements and allow the RHPS to operate in a grid-connected configuration.

**IMPACT:** The RHPS represents a significant advance toward development of roadway structures that use renewable sources to produce more energy than they consume. The RHPS will provide stable, reliable power to ensure that critical transportation system components operate safely and continuously during local or widespread power outages.



The renewable infrastructure of this project in place.  
© University of Nebraska-Lincoln.



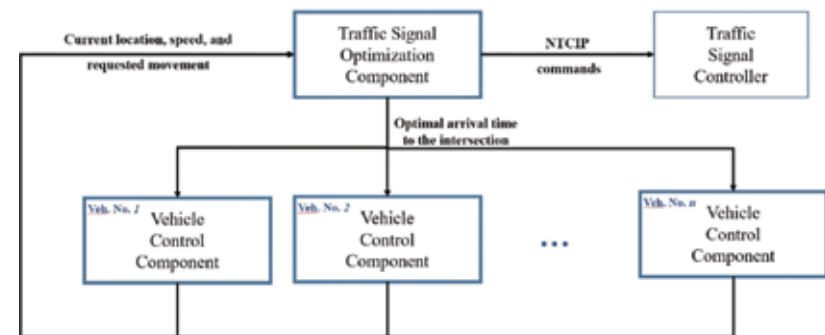
## RESULTS FROM RESEARCH ASSOCIATESHIP PROGRAM

The Federal Highway Administration (FHWA) participates in the National Research Council (NRC) Research Associateship Program (RAP) with other sponsoring Federal laboratories and approved research organizations. RAP provides highly skilled and exceedingly promising postdoctoral and senior scientists and engineers with opportunities to research problems that are compatible with the interests of sponsoring laboratories. To supplement the expertise of permanent staff, FHWA through its Exploratory Advanced Research (EAR) Program uses the RAP to invite researchers with appropriate backgrounds to investigate specific problems on a short-term basis across a range of topics and disciplines.

The associates have researched a variety of topics, such as nano-additives for concrete and asphalt, alternative intersection and interchange design, and cost-benefit analysis of connected and automated vehicle operations. Below is a summary of some of the research projects by focus areas that the resident associates have been involved in during their respective tenures at FHWA

For more details on the projects or to view a copy of the most recent version of the *EAR Program's Research Associates Program* booklet, please visit our publication Web page at <https://www.fhwa.dot.gov/publications/lists/advancedresearch/pubs.cfm>.

- PROJECT:** Cost-Benefit Analysis of Connected and Automated Vehicle Operations
- ASSOCIATE:** Mehdi Zamanipour
- SCHOOL:** University of Arizona
- PERIOD:** September 2016–
- OBJECTIVE:** To study the costs and benefits of deploying connected and automated vehicle (CAV) technology along signalized corridors and develop a tool to analyze the mobility and environmental benefits of deploying systems.
- ADVISER:** Govindarajan Vadakpat, FHWA Office of Operations R&D



The Proposed Integrated Signal and Trajectory Control Optimization Framework.  
© Mehdi Zamanipour.

**IMPACT:** Although the simulation environment in this project was created to analyze Multi-Modal Intelligent Traffic Safety System and GlidePath, it could be used to study other dynamic mobility applications such as cooperative adaptive cruise control. State and local transportation agencies could incorporate the tool into a larger, overall analysis framework to justify investments into CAVs. The results of the research also can help demonstrate the relationship between CAV market penetration and lower fuel consumption.





## Breakthrough Concepts in Materials Science

**PROJECT:** Comprehension and Development of Nano-Additives to Judicially Improve the Interfacial Region in Concrete and Asphalt

**ASSOCIATE:** Jose Muñoz

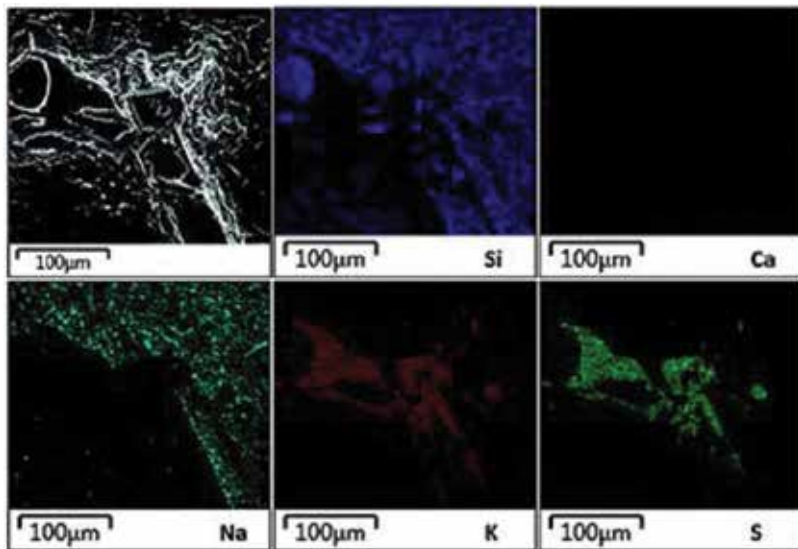
**SCHOOL:** University of Wisconsin–Madison

**PERIOD:** April 2010–March 2013

**OBJECTIVE:** To investigate how judicially applied coatings on the surface of the aggregates of different nano-additives can improve the interfacial region in concrete and asphalt.

**ADVISER:** Jack S. Youtcheff, FHWA Office of Infrastructure R&D

**IMPACT:** The development of new nano-additives, together with a new method for applying them in concrete, is expected to help create materials with less water and chloride penetrability and higher mechanical strength and resistance to cracking. This is expected to lead to the creation of construction materials with improved characteristics and less energy demand for maintenance operations.



Backscattered electron images of a potassium sulfate crystal formed inside of a silica gel in the interfacial transition zone. The 100 µm shown in the image is equivalent to 0.0039 inch. Source: FHWA.

## Human Behavior and Travel Choices



**PROJECT:** Operational and Safety Analyses of Alternative Intersection/Interchange Designs

**ASSOCIATE:** Nopadon Kronprasert

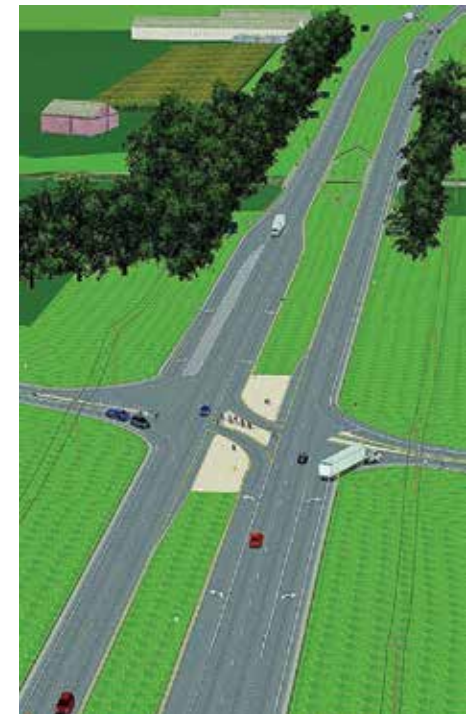
**SCHOOL:** Virginia Polytechnic Institute and State University

**PERIOD:** November 2012–April 2014

**OBJECTIVE:** To evaluate operational and safety impacts when implementing alternative intersection and interchange designs.

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

**IMPACT:** As of October 2014, at least one restricted-crossing U-turn and three mini-roundabouts Kronprasert worked on have been constructed and opened to traffic. Many of the performance predictions stated in his research are being verified in the field. The results will help analysts understand the relationships between the features of alternative designs and their operational and safety benefits. The research will ultimately help practitioners to find the best course of action when implementing alternate designs and will also help highway engineers and the public understand the benefits and impacts.



A screen capture of an intersection based on Nopadon Kronprasert's simulation input. Source: FHWA.



## **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.

The program has awarded 88 research projects on 50 different topics between 2007 and 2018. The research awards include work by multidisciplinary teams at 65 academic institutions, 44 private companies, 13 State and local agencies, 10 Federal laboratories, and 10 institutions outside the United States.

## **LEARN MORE**

For more information, see the EAR Program website at <http://highways.dot.gov/research/exploratory-advanced-research>. 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 the EAR Program is to apply ideas across traditional fields of research and stimulate new approaches to problemsolving. 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 Program 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, and deepening vital research capacity.