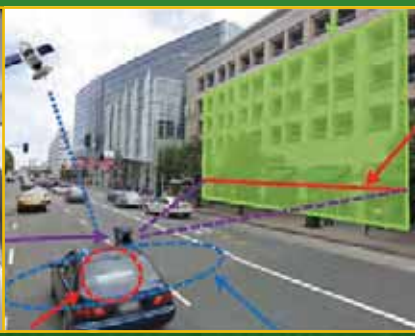
EXPLORATORY ADVANCED RESEARCH

EAR Program Research Results

Updated through 2016



U.S. Department of Transportation
Federal Highway Administration

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Cover photos

Left: *© SRI International. 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 22).*

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 11).*

EAR Program Research Results

Exploratory Advanced Research . . .
Next-Generation Transportation Solutions

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

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

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

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

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

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 eight solicitations, the EAR Program has awarded 79 projects (27 of which are ongoing as of September 2016) involving both government and academic researchers. These projects represent the investment of $76 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.

Contents

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

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., Bevly, 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.

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.

PROJECT: **Extended Event Horizon Navigation and Wayfinwding 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.

PROJECT: **Intersection Control for Autonomous Vehicles**

INSTITUTION: University of Texas at Austin

COMPLETED: 2013

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

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

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

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

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.

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

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

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.

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/~xuanyg/doc/Argote_Christofa_Xuan_Skabardonis_2012_TRB.pdf

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

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

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

INSTITUTION: University of Virginia Center for Transportation Studies

COMPLETED: 2012

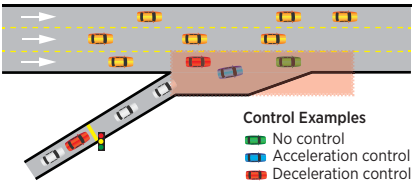
OBJECTIVE: To develop and evaluate candidate freeway merge-assistance systems that might improve the efficiency and safety of freeway merges in a connected vehicle environment.

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

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

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

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



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

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/

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

RESULTS: The project team developed an integrated vehicle positioning system in which subsystems with complementary strengths are fused to provide precise positioning data in environments where one or more of the subsystems could fail. The subsystems assessed were GPS; inertial navigation systems (INS); camera and 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.

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.

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

INSTITUTION: University of California, Riverside

COMPLETED: 2012

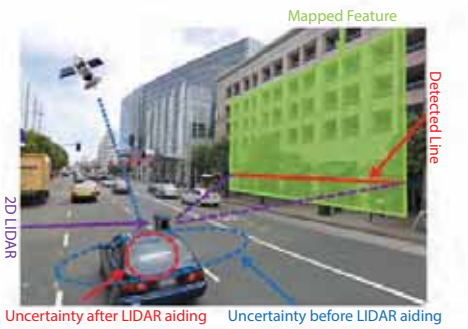
OBJECTIVE: To investigate and test a range of approaches that could provide lane-level positioning accuracy in diverse driving environments.

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

RESOURCE: Project details at http://www.fhwa.dot.gov/research/tfhrc/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 (LIDAR, radar, computer vision, and dedicated short-range communication [DSRC]), the research team developed and tested prototype systems that integrate a variety of sensors. The team found that LIDAR and radar technology integrate with the quickest processing and response, and terrestrial radio navigation and DSRC methods require more time. Radio and DSRC-based methods show great promise because implementation costs are relatively low, but require further development to improve accuracy. The performance of vision-based aiding improves with increased sensor cost; however, implementation requires development of onboard feature mapping.

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



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

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

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

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

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

RESOURCE: Final report at 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; achieved higher effective lane capacities using cooperative adaptive cruise control (CACC); and reduced fuel consumption and increased truck-only lane capacity with automated platoons.

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

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

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

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

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 http://www.fhwa.dot.gov/publications/research/safety/11056/11056.pdf

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

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

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.

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

RESOURCE: 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 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 (8 mm) and hooked-end steel macro fibers (30 mm) 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.

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 http://www.nrmca.org/research_engineering/Documents/Lab_fly_ashFinal_report.pdf

Presentation at http://webpages.mcgill.ca/staff/Group3/aboyd1/web/Conferences/AMW%20XI/Presentations/Meininger%20Rev.pdf

Fly ash with different carbon content levels.

RESULTS: Large-scale experiments demontrated 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.

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

INSTITUTIONS: Texas A&M University and Texas Transportation Institute

COMPLETED: 2011

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

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

RESOURCES: Technical report at http://d2dtl5nnlpfr0r.cloudfront.net/swutc.tamu.edu/publications/technicalreports/476660-00017-1.pdf

Research article at http://www.hindawi.com/journals/jnm/2012/371927

RESULTS: Investigators performed a comprehensive review of previous work using carbon nanofilaments (CNFs) and nanotubes (CNTs) in cementitious materials to improve their mechanical properties and behaviors, and conducted a detailed study of the common method of incorporating CNFs. The researchers 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.

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 2,000 terabytes of data.

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

Chu, W-S., de la Torre, F., Cohn, J., Selective Transfer Machine for Personalized Facial Expression Analysis, *IEEE Trans. Pattern Anal. Machine Intell., PP*(99).

Zeng, J., Chu, W-S., de la Torre, F, Xiong, Z., Confidence Preserving Machine for Facial Action Unit Detection, *IEEE Trans. Image Process.*, 2016, *25*(10):1-1.

Seshadri, K., 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., Akkas, O., *Are Driver Movement Patterns Indicators of Distraction and Engagement?* Proc. Human Factors 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.

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.

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 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 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.

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 non-reversible, ensuring that driver identity is protected. Researchers have developed an automatic graphical user interface that can output de-identified video.

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.

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 identify is protected using an avatar to replace their face in all frames.

Human Behavior and Travel Choices

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

INSTITUTION: University of Southern California

COMPLETED: 2014

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

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

RESOURCE: Project details at http://www.fhwa.dot.gov/research/tfhrc/projects/projectsdb/projectdetails.cfm?projectid=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 are.

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.

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.

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

RESOURCE: 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 researchers delivered a set of comprehensive modeling tools and a revolutionary system for a multi-agent modeling system 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=F-HWAPROJ-12-0070

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

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

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 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 to accurately rendering the visual complexity of the roadway, will lead drivers in the simulator to drive at speeds quite comparable to those observed on actual roadways.

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

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

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

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

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

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

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 R&D

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

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

IMPACT: This project provides the framework and tools for 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

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

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

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

Human Behavior and Travel Choices

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

INSTITUTIONS: Arizona State University, University of Arizona, 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 Web site at http://urbanmodel.asu.edu/intmod.html

RESULTS: SimTRAVEL, developed in this project, is an integrated modeling system that advances land-use and transportation microsimulation by providing seamless modeling of longer term choices about location (home, work 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

PROJECT: **Remotely Monitoring Water Quality Near Highways: A Sustainable Solution**

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: **Marcel Tchaou,** FHWA Office of Project Development and Environmental Review

RESOURCES: 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

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 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., et al., Passive Wireless Antenna Sensor for Strain and Crack Sensing—Electromagnetic Modeling, Simulation, and Testing, *Smart Materials Structures*, 2013, *22*, 085009, at http://iopscience.iop.org/0964-1726/22/8/085009/

Yi, X., 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

Project details at http://www.fhwa.dot.gov/research/tfhrc/projects/projectsdb/projectdetails.cfm?projectid=F-HWA-PROJ-10-0014

Antenna sensor tracking crack propagation.

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.

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.

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

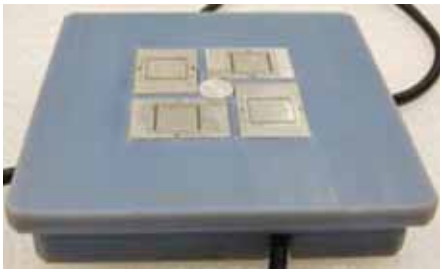
OBJECTIVE: To advance technology for measuring and understanding the complex flow fields and boundary shear stresses and pressure fields associated with bridge pier scour.

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 ±100 Pa, with a sampling rate of more than 500 data points per second. Such a system will help researchers understand erosive flow mechanisms related to turbulence structures, together with local flow convergence and contractions around the fronts and flanks of piers or between piles of complex pier configurations. Direct measurements of shear forces are essential to validated computational fluid dynamic models.

IMPACT: Scour is the 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.

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.

Strain guages, 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.

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.

New Technology and Advanced Policies for Energy and Resource Conservation

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., 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., et. al. 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.

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.

Roadway Wind/Solar Hybrid Power Generation and Distribution System (RHPS) in place.

GETTING INVOLVED WITH THE EAR PROGRAM

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

LEARN MORE

For more information, see the EAR Program Web site at www.fhwa.dot.gov/advancedresearch. 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 problem solving. The program bridges basic research (e.g., academic work funded by National Science Foundation grants) and applied research (e.g., studies funded by State departments of transportation). In addition to sponsoring EAR 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.

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