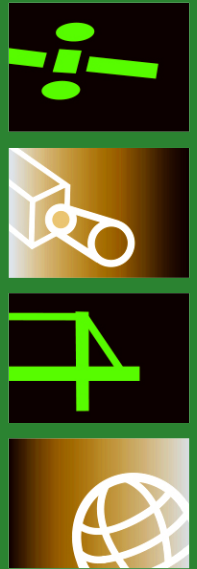
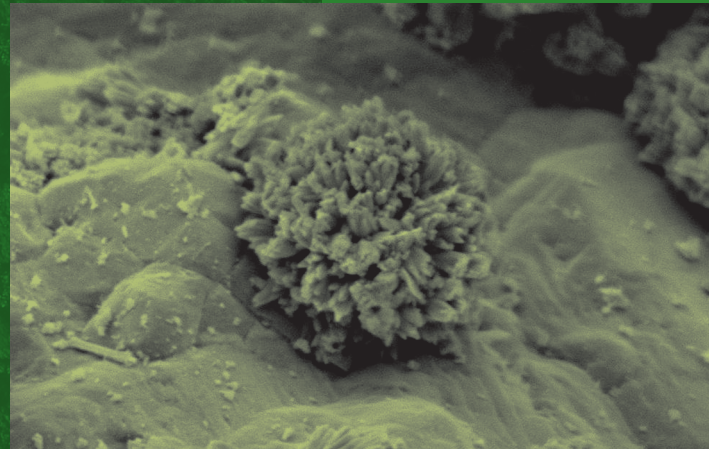
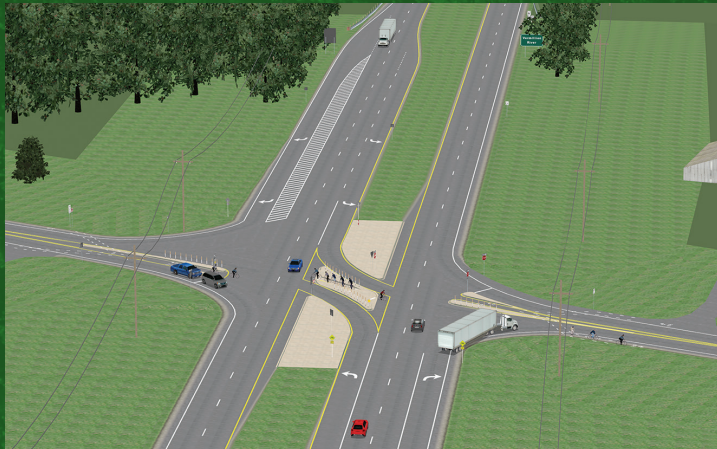


Exploratory Advanced Research Program **Research Associates Program 2021**



EXPLORATORY ADVANCED RESEARCH



U.S. Department of Transportation
Federal Highway Administration

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Cover photos

Left: A simulation input illustrates former EAR Program research associate Nopadon Kronprasert's work on alternative intersection and interchange designs.

Right: Image showing the nucleation of ettringite mineral in the interfacial transition zone, part of a research objective to develop inorganic curing compounds for addressing the shortcomings of current organic membrane-forming curing compounds in pavement construction.

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The Research Associateship Program

Since 1954, the National Research Council (NRC) has conducted the Research Associateship Program (RAP) in cooperation with sponsoring Federal laboratories and other approved participating 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. RAP offers recent doctoral graduates opportunities for concentrated research with selected members of permanent, professional, laboratory staff and allows them to contribute to the overall efforts of the laboratories.

The Federal Highway Administration (FHWA) has participated in RAP since 1992. To supplement the expertise of permanent staff, FHWA's Turner-Fairbank Highway Research Center (TFHRC), through its Exploratory Advanced Research (EAR) Program, invites researchers with appropriate backgrounds to investigate specific problems on a short-term basis across a wide range of topics and disciplines.

NRC provides a process for selecting candidates on a competitive merit basis and, subsequently, for administration of the resident fellows during their tenures at FHWA. The process begins with a prospective FHWA adviser developing a proposed research opportunity. The adviser then coordinates with FHWA leadership to approve the opportunity and forward the proposed research to NRC. All research opportunities require an abstract that relates to exploratory advanced research and is of specific relevance to the FHWA research program. One of the significant benefits of this process is that it encourages interaction between government researchers and new researchers who are using cutting-edge approaches and research tools in their work.

RAP provides opportunities for FHWA's EAR Program to advance research methods used at TFHRC. Over the years, associates have researched topics as diverse as cost-benefit analysis of connected and automated vehicle operations, nano-additives for concrete and asphalt, alternative intersection and interchange design, and modeling to predict collisions based on driver behavior and environmental conditions.

The following pages contain summary descriptions of some of the research projects that the resident fellows have been involved in during their respective tenures at FHWA.

EXPLORATORY ADVANCED RESEARCH



The EAR Program sponsors longer term, higher risk research, leveraging cutting-edge science and engineering as well as top-notch expertise to create breakthrough solutions to highway transportation-related issues.



Breakthrough Concepts in Materials Science

PROJECT: Development and Evaluation of Innovative Structural Systems with UHPC and Resilient Connections: From Analyses and Experiments to Design Guidelines

ASSOCIATE: Alireza Mohebbi

SCHOOL: University of Nevada, Reno

PERIOD: April 2018–September 2021

OBJECTIVE: To investigate the time-dependent properties of ultra-high performance concrete (UHPC).

ADVISER: Ben Graybeal, FHWA Office of Infrastructure Research and Development

SUMMARY: Alireza Mohebbi investigated the time-dependent properties of UHPC and conducted small-scale and large-scale testing in the FHWA-TFHRC Concrete and Structures laboratories. He developed new predictive models for creep coefficient and shrinkage strain of UHPC-class materials. Mohebbi also investigated and developed a prestress loss model for pretensioned UHPC girder. The predictive models were included in the UHPC structural design guide draft submitted to the AASHTO-T10 Concrete Design Technical Committee of the Subcommittee on Bridges and Structures for adoption in AASHTO LRFD Bridge Design Specifications.

RESOURCES: Several publications and papers resulted from this RAP research. They are outlined below.

Mohebbi, A., Z. Haber, and B. Graybeal. 2019. "Evaluation of AASHTO Provisions for Creep and Shrinkage of Prestressed UHPC Girders." Presented at the 2nd International Interactive Symposium on UHPC. Albany, NY.

Mohebbi, A., R. El-Helou, and B. Graybeal. 2019. "End Zone Design and Behavior of Prestressed UHPC Girders." Presented at the International Accelerated Bridge Construction Conference. Miami, FL: Accelerated Bridge Construction University Transportation Center.



Breakthrough Concepts in Materials Science

PROJECT: Integrating Lifecycle Thinking into Current Pavement Practices

ASSOCIATE: Milena Rangelov

SCHOOL: Washington State University

PERIOD: January 2019–June 2021

OBJECTIVE: To develop lifecycle assessment (LCA) for pavements and pavement materials in a manner that supports data-driven decision making and lifecycle thinking.

ADVISER: Nadarajah Sivanewaran, FHWA Office of Infrastructure Research and Development

SUMMARY: Milena Rangelov's research included the development and advancement of LCA for pavements and pavement materials in a manner that supports data-driven decision making and lifecycle thinking. Specific areas of work and clarification of projects and contributions are described as follows:

- Integration of LCA into planning and project delivery for pavements: This project included collaborative work with stakeholders to outline the current pavement design, planning process, and decision making and evaluate LCA fit in a way that facilitates the reduction of environmental impacts. Later phases of the project also included the integration with asset management.
- Use of environmental product declarations to support green public procurement (GPP): This study involved a national scan of current environmental product declarations and product category rules for pavement construction materials and investigated their use to support current and future efforts in GPP. The results of this study indicate the need for harmonization and standardization to provide a solid framework for achieving environmental impact reductions.
- Environmental impacts of the use of secondary materials in pavements: Even though the use of secondary and recycled materials in pavements is typically considered to be a sustainable practice, quantification of environmental impacts is necessary to support claims about sustainability. This study investigated methodological frameworks and approaches for secondary-materials allocation and their benefits and tradeoffs.
- LCA of asphalt pavements: Two studies done under this scope include the study of the use of recycled polyethylene in asphalt pavements and the use of ground tire rubber (GTR). The first study was focused on the synergies between engineering and environmental performance, aiming to document what level of performance is needed to achieve environmental benefits with recycled polyethylene. The second study was performed for the Puerto Rico case because the island grapples with the problem of excess waste tires. Two levels of analysis, at the pavement and system level, showed what drives the environmental performance of GTR-modified mixes and how much pavements can help alleviate the waste-tire problem for Puerto Rico.
- LCAs of concrete pavements and structures: The first study from this domain includes the LCA of UHPC bridge deck overlay in comparison to conventional solutions such as portland cement concrete and latex-modified concrete from a lifecycle perspective. The second study follows the efforts of the Mobile Concrete Technology Center. By performing LCA for mixture designs collected over the last decade across the United States, this study sheds light on opportunities for agencies to reduce the environmental



Breakthrough Concepts in Materials Science

footprint of concrete pavements.

RESOURCES: Several publications and papers resulted from this RAP research. They are outlined below.

Rangelov, M., H. Dylla, A. Mukherjee, and N. Sivanewaran. 2020. "Use of Environmental Product Declarations (EPDs) of Pavement Materials in the United States of America (U.S.A.) to Ensure Environmental Impact Reductions." *Journal of Cleaner Production* 283: 24619.

Rangelov, M., H. Dylla, N. Sivanewaran, and J. Davis. 2020. "Integration of Life Cycle Assessment into Planning And Project Delivery for Pavements in the USA." *The International Journal of Life Cycle Assessment* 25: 1605-1619.

Rangelov, M., S. Nassiri, and K. Englund. 2020. "Life Cycle Assessment of Pervious Concrete Pavements Reinforced by Recycled Carbon Fiber Composite Elements, Pavement, Roadway, and Bridge Life Cycle Assessment." Presented at the International Symposium on Pavement, Roadway, and Bridge Life Cycle Assessment. Sacramento, CA: University of California Pavement Research Center and the National Center for Sustainable Transportation.

Rangelov, M., R. Spragg, Z. Haber, and H. Dylla. 2020. "Life Cycle Assessment of Ultra-High Performance Concrete Bridge Deck Overlays, Pavement, Roadway, and Bridge Life Cycle Assessment." Presented at the International Symposium on Pavement, Roadway, and Bridge Life Cycle Assessment. Sacramento, CA: University of California Pavement Research Center and the National Center for Sustainable Transportation.

Rangelov, M., H. Dylla, and N. Sivanewaran. 2020. "Using environmental product declarations to support pavement green public procurement, Pavement, Roadway, and Bridge Life Cycle Assessment." Presented at the International Symposium on Pavement, Roadway, and Bridge Life Cycle Assessment. Sacramento, CA: University of California Pavement Research Center and the National Center for Sustainable Transportation.



Breakthrough Concepts in Materials Science

PROJECT: Novel Applications of UHPC in Bridge Structures

ASSOCIATE: Arash E. Zaghi

SCHOOL: University of Nevada, Reno

PERIOD: May 2019–May 2020

OBJECTIVE: Develop novel applications of UHPC in bridge structures.

ADVISER: Benjamin Graybeal, FHWA Office of Infrastructure Research and Development

SUMMARY: Arash Zaghi, an associate professor at the University of Connecticut at the time, refined and optimized the current tensile testing method for UHPC material. He developed a finite element simulation methodology for structural elements made of UHPC material. Zaghi also advanced a novel repair method for distortion-induced fatigue in steel bridges and performed large-scale experiments to validate the repair concept. In his work, Zaghi investigated the applicability of a simplified testing method for multimode fracture behavior of UHPC.

RESOURCES: Several publications and papers resulted from this RAP research. They are outlined below.

Graybeal, B., E. Brühwiler, B.-S. Kim, F. Toutlemonde, Y. L. Voo, A. Zaghi. 2020. "International Perspective on UHPC In Bridge Engineering." *Journal of Bridge Engineering* 25, no. 11.

McMullen, K., and A.E. Zaghi. 2020. "Accelerated Repair of Corroded Steel Bridge Girders with Ultra-High Performance Concrete." Presented at 99th Annual Meeting of the Transportation Research Board. Washington, DC: Transportation Research Board.



Breakthrough Concepts in Materials Science

PROJECT: Ultra-High Performance Concrete: A Pathway to Resilient Infrastructure Systems through Material Characterization and Structural Design

ASSOCIATE: Rafic El-Helou

SCHOOL: Virginia Polytechnic Institute and State University

PERIOD: December 2016–October 2019

OBJECTIVE: To develop material testing standards, construction practices, and design methodologies for UHPC, and to advance innovative structural applications that fully use UHPC's durability and performance characteristics.

ADVISER: Benjamin Graybeal, FHWA Office of Infrastructure Research and Development

SUMMARY: UHPC has many advantages over conventional concrete, including greater strength, ductility, and resistance to corrosion, chemicals, and severe environmental conditions. Rafic El-Helou's research aimed to standardize material testing protocols, establish design models, and explore the best construction practices for UHPC. The nature of UHPC requires detailed standards to assess material behaviors like first cracking, postcracking behavior in tension, compression, and ductility. This standardization minimizes variations in material data and foster the development of characteristic design models for UHPC. To pursue those goals, El-Helou built a national database of UHPC material testing procedures and experimental data, performing material tests that explore UHPC characteristics, assessing the applicability of current testing methods to UHPC, and developing design guides and codes that include material models and structural design methods for UHPC. Prototyping of pretensioned bridge girders built with UHPC was also part of El-Helou's project. This effort was intended to validate that increasing the span range of concrete bridges can be achieved with UHPC.

IMPACT: El-Helou took part in FHWA efforts to develop and deliver a draft on UHPC for the American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) Bridge Design and Construction Guide Specifications. This work will support AASHTO's interest in producing a national UHPC standard through its Committee on Bridges and Structures, Subcommittee T-10. El-Helou's research on material testing standards, design methodologies, and construction practices will encourage simplicity, speed, and creativity in designing and implementing UHPC. His investigation also provides suggestions on optimal use of UHPC in innovative highway applications.

RESOURCES: Several publications and papers resulted from this RAP research. They are outlined below.

Haber, Z. B., I. De La Varga, B. Graybeal, B. Nakashoji, and R. El-Helou. 2018. Properties and Behavior of UHPC-Class Materials. Report No. FHWA-HRT-18-036. Washington, DC: Federal Highway Administration.

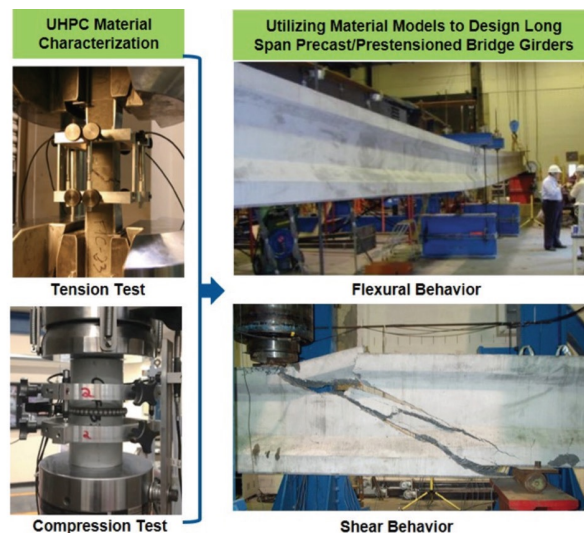
Graybeal, B., and R. G. El-Helou. 2018. "AASHTO LRFD design and Construction Guide Specification For Ultra-High Performance Concrete, FHWA-TFHRC Plan Towards Development and Delivery." Presented at the AASHTO Committee on Bridges and Structures (CBS) T-10 Committee Meeting. Burlington, VT: American Association of State Highway and Transportation Officials.

El-Helou, R. G., and B. Graybeal. 2018. "Towards Ultra-High Performance Concrete Design Guidance In The United States." Presented at the American Concrete Institute Spring 2018 Convention. Salt Lake City, UT: American Concrete Institute.

El-Helou, R. G., and B. Graybeal, B. 2017. "AASHTO LRFD Design and Construction Guide Specification For Ultra-High Performance Concrete, Models and Design Concepts: Compression, Tension, Flexure, And 300 Ft Pretensioned Girder." Presented at the Transportation Pooled Fund Solicitation TFP-5(366) Kickoff Meeting. Ames, IA: Federal Highway Administration.

Graybeal, B., and R. G. El-Helou. 2017. "AASHTO LRFD Design and Construction Guide Specification for Ultra-High Performance Concrete, FHWA-TFHRC Plan Towards Development And Delivery." Presented at the AASHTO Subcommittee on Bridges and Structures (SCOBs) T-10 Committee Meeting, Cleveland, OH: American Association of State Highway and Transportation Officials.

These images illustrate the process for developing and evaluating UHPC bridge design methods. Source: FHWA.





Breakthrough Concepts in Materials Science

PROJECT: Shear Performance of Full-Scale Pretensioned UHPC Bridge Girders

ASSOCIATE: Gary Greene

SCHOOL: Missouri University of Science and Technology

PERIOD: May 2019–August 2019

OBJECTIVE: To apply engineering research to advance the state-of-the-art in concrete highway bridges.

ADVISER: Benjamin Graybeal, FHWA Office of Infrastructure Research and Development

SUMMARY: Gary Greene, a professor at Trine University at the time, led the setup and execution of large-scale structural tests on concrete bridge girders within the FHWA Structural Testing Laboratory. He employed his extensive experimentalist skills to complete a novel testing program that investigated the next generation of concrete, UHPC, under unique loading conditions for primary structural behaviors.



Breakthrough Concepts in Materials Science

PROJECT: Modeling of Pavement Response Under Traffic Speed Deflection Devices for Pavement Management Application

ASSOCIATE: Seyyedmahdi Nasimifar

SCHOOL: University of Nevada–Reno

PERIOD: April 2016–January 2019

OBJECTIVE: To develop robust methods to relate traffic speed deflection device (TSDD) measurements to pavement structural responses for assessing pavement structural condition and rate of deterioration.

ADVISER: Nadarajah Sivanewaran, FHWA Office of Infrastructure Research and Development

SUMMARY: Seyyedmahdi “Mahdi” Nasimifar developed an analytical approach that is designed to advance the incorporation of TSDDs, specifically the Rolling Wheel Deflectometer (RWD) and the Traffic Speed Deflectometer (TSD), into pavement management applications. To help achieve his research objective, he used 3D-Move, a software tool developed under an FHWA research effort, which models loads as they move across pavements and computes the resulting pavement responses. Nasimifar’s current project is an outgrowth of his previous work with 3D-Move as a member of a team that carried out an FHWA-sponsored project evaluating the RWD and TSD through field trials at the Minnesota Road Research Facility and analytical modeling. Nasimifar used data collected at the field trials and TSD data collected on pavement sections in several States that participated in an FHWA-led transportation pooled-fund study to calibrate his analytical model. With the calibrated model, he developed correlations that related critical pavement responses such as tensile strains at the bottom of the asphalt layer (fatigue) and compressive strains at the top of subgrade (rutting) to TSDD measurements and pavement layer properties. He also conducted sensitivity analyses to identify the best correlations between TSDD measurements and pavement responses. The final step was validating the results from the new model against the field measurements to illustrate that it can be applied at a system-wide level. Nasimifar thoroughly investigated all parameters that could affect the analytical model, from the viscoelastic properties of the asphalt-concrete layer to moving-load properties and unbound pavement layer properties. In addition, he developed a robust and

practical method to adjust the surface curvature index from TSD data to a reference temperature and proposed a method to use TSD data to estimate the effective structural number. This can be used to determine remaining structural life and rank pavement sections for improvements, maintenance, and rehabilitation.

IMPACT: Building upon previous FHWA-sponsored research into TSDDs, Nasimifar is working toward better methods for evaluating pavement structural condition and the rate at which it deteriorates. Studies have shown that incorporating pavement structural condition into the decisionmaking process for pavement management leads to better-informed decisions and more cost-effective pavement rehabilitation and preservation strategies. Nasimifar’s effort will enable State highway agencies to incorporate pavement structural condition into their pavement management systems to predict how traffic and environmental loads will affect their pavement networks over time and better plan treatment types and timing to optimize investment decisions. The Virginia Tech Transportation Institute, the research team for a new transportation pooled-fund study, is using a tool that incorporates Nasimifar’s research for analyzing the TSD data collected as part of the project.

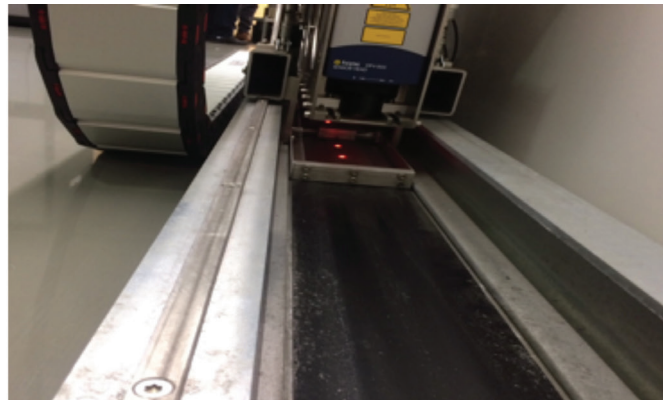
ONGOING RESEARCH: With the development of TSDDs, network-level assessment of pavement structural condition has become practical. The application of structural condition data in pavement management systems can increase the robustness of structural deterioration models. A comprehensive study on improving the pavement deterioration models that include structural condition



The traffic speed deflectometer is a trailer truck that measures pavement dynamic responses while traveling at traffic speed. © 2018 Seyyedmahdi Nasimifar.



Breakthrough Concepts in Materials Science



is under investigation. The results of this study will enable State highway agencies to use enhanced pavement deterioration models that will foster more informed treatment selections and timing and will maximize the benefits from the investments being made.

RESOURCES: Several publications and papers resulted from this RAP research. They are outlined below.

- Nasimifar, M., Thyagarajan, S., & Sivaneswaran, N. (2018). Computation of pavement vertical surface deflections from traffic speed deflectometer data—Evaluation of current methods. *Journal of Transportation Engineering, Part B: Pavements*, 144(1), 04018001.
- Nasimifar, M., Thyagarajan, S., & Sivaneswaran, N. (2017). Backcalculation of flexible pavement layer moduli from traffic speed deflectometer data. *Transportation Research Record: Journal of the Transportation Research Board*, 2641, 66–74.
- Nasimifar, M., Thyagarajan, S., & Sivaneswaran, N. (2017). *Comparison of the methodologies to compute pavement surface deflections from traffic speed deflectometer data*. Presented at the World Conference on Pavement and Asset Management, Milan, Italy.

Internal pavement response measure instrumentation of the Traffic Speed Deflectometer.
© 2018 Seyyedmahdi Nasimifar.

- Nasimifar, M., Thyagarajan, S., Chaudhari, S., & Sivaneswaran, N. (2018). *Evaluation of temperature correction models for deflection index from falling weight deflectometer and traffic speed deflectometer*. Presented at the 97th Transportation Research Board Annual Meeting, Washington, DC.
- Nasimifar, M., Thyagarajan, S., & Sivaneswaran, N. (2017). *Backcalculation of flexible pavement layer moduli from traffic speed deflectometer data*. Presented at the 96th Transportation Research Board Annual Meeting, Washington, DC.
- Nasimifar, M. (2016). *Using traffic speed deflectometer data to back-calculate pavement layer moduli*. Presented at the Falling Weight Deflectometer Users Group, San Jose, CA.



Breakthrough Concepts in Materials Science

PROJECT: Providing a Performance-Based Asphalt Mixture Design Framework through Fatigue and Thermal Cracking Index Parameters

ASSOCIATE: David Mensching

SCHOOL: University of New Hampshire

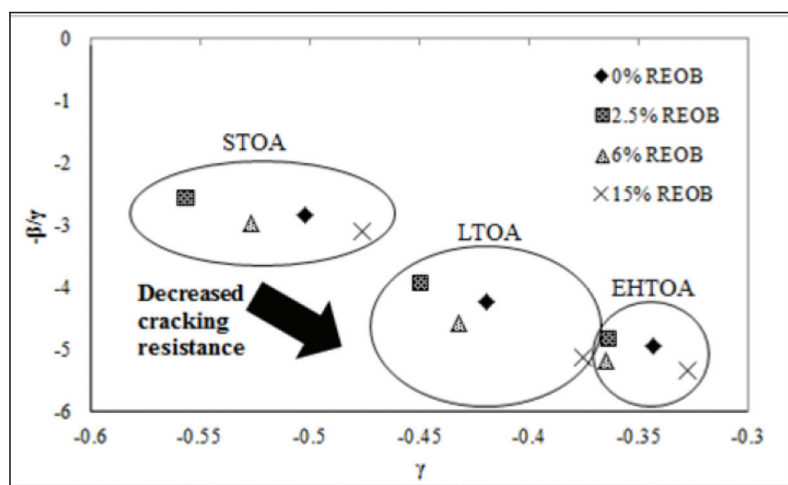
PERIOD: May 2015–August 2016

OBJECTIVE: To develop index parameters to relate material and structural parameters, identifying whether a mixture is prone to fatigue or thermal cracking.

ADVISER: Nelson Gibson, FHWA Office of Infrastructure Research and Development

SUMMARY: The premature distress and failure of highways cost money in the form of repairs and time in the form of increased congestion while repairs are being made. One way to alleviate these effects is to improve the science behind pavement design, including the proportion of asphalt, additives, and aggregates for creating performance-based mixtures. David Mensching's research explored ways to revise, enhance, and expand the index parameters for informing the design decisions of highway departments and contractors. An index parameter compares a specialized value (or index) to a critical threshold for failure of a material. In this case, Mensching used index parameters to gauge the impact of content, gradation, and air voids on asphalt mixtures, with an eye toward impeding thermal and fatigue cracking. The project consisted of testing various asphalts in the

field and developing a database to monitor degradation and volumetric changes in pavement over time. The field methods included dynamic modulus testing to develop a framework for creating Black Space diagrams, a physics tool for evaluating the elasticity and stiffness of materials, and direct tension fatigue tests using the simplified viscoelastic continuum damage model. Mensching used FHWA's Accelerated Loading Facility at the TFHRC and the Asphalt Mixture Performance Tester to monitor performance. To develop a materials database that could reflect regional differences in pavement materials and predict their performance, he collected information from WesTrack in Nevada and from departments of transportation.



This beta-gamma plot compares conventional, short-term oven aging (STOA) for asphalt with loose-mix, long-term oven aging (LTOA) and extended, high-temperature oven aging (EHTOA). Varying amounts of re-refined engine oil bottoms (REOB) are used. Cracking resistance is expected to decrease as beta/gamma decreases and gamma increases. The plot shows that EHTOA is more extreme than LTOA and that 15 percent REOB is in a less crack-resistant location than the other mixtures.

From: Mensching, D., A. Andriescu, C. DeCarlo, et al. 2017. "Effect of Extended Aging on Asphalt Materials Containing Re-Refined Engine Oil Bottoms." Transportation Research Record 2632, no. 1: 10. copyright © 2017 by David Mensching. Reprinted by permission of SAGE Publications, Inc.



Breakthrough Concepts in Materials Science

IMPACT: Mensching's research benefitted FHWA's initiative on performance-based asphalt designs in multiple ways. His research work showed how different asphalts perform based on temperature changes and fatigue stresses. His study also expanded national data about asphalt materials and soil structures for future research as well as the usefulness of Black Space diagrams to gauge the performance of asphalt mixtures and monitor pavement degradation. He generated a report to help highway departments and contractors adjust asphalt designs based on temperature, fatigue, and rutting performance.

RESOURCES: Several publications and papers resulted from this RAP research. They are outlined below.

- Mensching, D. J. (2016). *Testing for fatigue cracking in the asphalt mixture performance tester*, Report No. FHWA-HIF-16-027, Federal Highway Administration, Office of Asset Management, Pavement, and Construction, Washington, DC.
- Mensching, D. J., Rahbar-Rastegar, R., Underwood, B. S., & Daniel, J. S. (2016). Identifying indicators for fatigue cracking in hot mix asphalt pavements using viscoelastic continuum damage principles. *Transportation Research Record: Journal of the Transportation Research Board*, 2576, DOI: 10.3141/2576-04.
- Jeong, M. M., & Mensching, D. J. (2017). Testing and acceptance procedures for as-constructed asphalt mixtures related to thermal fracture. *Journal of Transportation Engineering: Part B, Pavements*, 143(4).
- Mensching, D. J., Andriescu, A., DeCarlo, C., Li, X., & Youtcheff, J. S. (2017). Effect of extended aging on asphalt materials containing re-refined engine oil bottoms. *Transportation Research Record: Journal of the Transportation Research Board*, 2632, DOI: 10.3141/2632-07.
- Li, X., Mensching, D. J., & Gibson, N. H. (2017). A practical method to determine the strain level for cyclic direct tension fatigue testing in the AMPT. *Transportation Research Record: Journal of the Transportation Research Board*, 2631, DOI: 10.3141/2631-15.
- Mensching, D. J., Jeong, M. M., & McCarthy, L. M. (2016). Relative comparison of complex dynamic modulus predictive models for non-conventional asphalt concrete mixes. *Journal of Testing and Evaluation*, 46(1).
- Mensching, D. J., Gibson, N. H., Andriescu, A., Rowe, G. M., & Daniel, J. S. (2016). *Assessing the applicability of rheological parameters to evaluate modified binders*. Presented at the International Society for Asphalt Pavements Symposium, Jackson Hole, WY.
- Mensching, D. J., Gibson, N. H., Rowe, G. M., & Daniel, J. S. (2016). *Using mixture-based rheology to evaluate cracking performance of modified asphalt pavements*. Presented at the International Society for Asphalt Pavements Symposium, Jackson Hole, WY.



Breakthrough Concepts in Materials Science

PROJECT: Developing Frameworks of Performance-Based Asphalt Mix Design

ASSOCIATE: Jong-Sub Lee

SCHOOL: North Carolina State University

PERIOD: September 2014–April 2016

OBJECTIVE: To investigate use of mechanistic models to evaluate voids in mineral aggregate (VMA), design air void content, and in-place air void content as parameters for reliably predicting field performance of various asphalt mix designs.

ADVISER: Katherine Petros, FHWA Office of Infrastructure Research and Development

SUMMARY: Performance-related specifications (PRS) will offer engineers, contractors, and funding agencies a way to assess future performance, maintenance requirements, and lifecycle costs for highway construction projects. PRS can be thought of as a set of quality assurance specifications that describe the desired levels of key materials and construction-acceptance quality characteristics that correlate with fundamental engineering properties that predict performance. PRS will rely on models that objectively assess performance based on observed construction-quality characteristics related to fundamental engineering properties and will:

- Utilize testing that focuses on key measureable characteristics related to performance.
- Use pavement design assumptions as a basis for construction performance.
- Incorporate incentives and disincentives based on modeled performance.
- Allow contractors to innovate and be competitive.
- Reduce long-term monitoring and management.

When fully developed, PRS will employ the quantified relationships containing the characteristics to predict as-constructed pavement performance. Thus, PRS will provide the basis for rational acceptance and pay-adjustment decisions related to highway construction projects.

Jong-Sub Lee's research helped develop a testing and modeling framework for performance-based asphalt mix design. The goal was to identify the effect of volumetric mix design targets (design VMA and design air void) and compaction level (in-place air density) on fatigue characteristics and performance. The project investigated asphalt mixtures based on the Superpave® mix design system (developed through the Strategic Highway Research Program) using mechanistic analyses based on the viscoelastic continuum damage (VECD) analyses and mechanistic-empirical pavement analysis using the AASHTOWare Pavement ME Design® program. The analyses included the simplified VECD model at the material level and

two structural models: (a) layered viscoelastic analysis and (b) layered viscoelastic pavement analysis for critical distresses.

Key performance-related findings of the research include:

- The damage state at failure is increased (i.e., better fatigue performance) with an increase in the design VMA and a decrease in the in-place air void and design air void content. The design VMA is more sensitive than the others.
- Fatigue life was found to improve when the value of the design VMA was increased and the in-place air void content and design air void content was decreased in rank of sensitivity.
- Superpave® mix design parameter of design VMA was the most sensitive parameter that significantly affected the linear viscoelastic property, damage characteristic, and fatigue life in the mechanistic analysis.
- The effect of the design air void on mechanistic fatigue life was diminished as the pavement thickness increased.
- Increasing the design VMA content caused the least amount of fatigue cracking area at the thin pavement.

IMPACT: Data gathered through this research will contribute to the development of testing and modeling protocols that can be used to develop PRS for asphalt mix design.

RESOURCES: The following reports resulted from this RAP research and are outlined below.

- Lee, J., Norouzi, A., & Kim, Y. R. (2016). Determining specimen geometry of cylindrical specimens for direct tension fatigue testing of asphalt concrete. *Journal of Testing and Evaluation*, 45(2).
- Lee, J-S., Gibson, N., & Kim, Y. R. (2015). Use of mechanistic models to investigate fatigue performance of asphalt mixtures: effects of asphalt mix design targets and compaction. *Transportation Research Record, Journal of the Transportation Research Board*, 2507.
- Lee, J-S., & Kim, Y. (2014). Performance-based moisture susceptibility evaluation of warm-mix asphalt concrete through laboratory tests. *Transportation Research Record, Journal of the Transportation Research Board*, 2446.
- Balis, J., & Platte, K. (n.d.). Performance specifications to speed construction, reduce oversight, and encourage innovative approaches: Performance specifications for rapid renewal (R07). *SHRP2 Solutions*.



Breakthrough Concepts in Materials Science

PROJECT: Tensile Response of Ultra-High Performance Concrete: Validation of Characterization Methods

ASSOCIATE: Luis Felipe Maya Duque

SCHOOL: Polytechnic University of Madrid

PERIOD: June 2013–April 2016

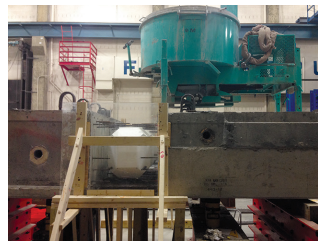
OBJECTIVE: To critically assess the applicability of a recently proposed tensile-test method for ultra-high performance, fiber-reinforced concrete.

ADVISER: Benjamin Graybeal, FHWA Office of Infrastructure Research and Development

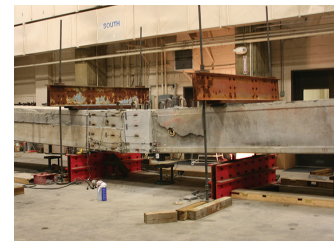
SUMMARY: Concrete is the most widely used construction material and has played a fundamental role in the development of infrastructure since the Romans. Advances in fiber-reinforced concretes over the last 50 years have enabled the development of an entirely new generation of cement-based composite materials. Ultra-high performance concrete (UHPC) represents a class of cement composites with high compressive strength and whose tensile response is characterized by high-strain capacity accompanied by multiple microcracking. To take full advantage of the tensile behavior of these UHPC materials, it is necessary to develop tensile-test methods and guidelines to be incorporated into codes and recommendations. Luis Felipe Maya Duque's research project focused on the assessment of proposed test methods designed to provide a reliable assessment of UHPC tensile behavior, not only in a research environment, but also for quality-control purposes in a production environment. Maya Duque assessed a singular direct tensile-test method that has already been the subject of FHWA research to establish advantages and drawbacks compared with existing methods. Maya Duque also conducted a critical review of the state of the art in tensile-test methods for UHPC. The research project included an extensive experimental campaign to properly assess the performance of the proposed tensile-test method. Furthermore, Maya Duque also considered the suitability of the direct tension test method to accurately reflect the influence of the fiber distribution and orientation in structural elements.

IMPACT: This research allows for the development and implementation of a quality control test method for UHPC in a production environment. Broader use of UHPC could lead to more durable and longer lasting highway structures, reducing the cost and risks associated with reconstruction.

ONGOING RESEARCH: FHWA conducted over 120 direct tension tests on both mold-cast and sawed specimens to assess the influence of flow conditions, as well as fiber orientation and fiber distribution on the tensile response of UHPC. FHWA also performed flexural tests on UHPC strips and slabs to correlate the results from the material characterization tests with the mechanical



Casting of beam splice connection.



Full-scale flexural test of a beam splice connection made of UHPC.

response of structural elements. Those results will contribute to assessing the reliability of the current design approaches as well as to improving understanding of the main mechanisms and variables to be considered in the development of design codes and recommendations. Maya Duque continues to complete the assessment of the structural efficiency of fiber reinforcement in UHPC structures through an experimental and analytical validation process at FHWA. FHWA plans to conduct two full-scale beam tests at the TFHRC Structures Laboratory. The results of these tests will provide insight for the development of continuity connection using UHPC as an alternative to increase the span range currently covered by conventional, precast, prestressed concrete girders.

RESOURCES: Several publications and papers resulted from this RAP research. They are outlined below.

Graybeal, B., & Baby, F. (2013). Development of a direct tension test method for ultra-high-performance fiber-reinforced concrete. *ACI Materials Journal*, 110(2), 177–186.

Maya, L. F., Zanuy, C., Albajar, L., Lopez, C., & Portabella, J. (2013). Experimental assessment of connections for precast concrete frames using ultra high performance fiber reinforced concrete. *Construction and Building Materials*, 48(11), 173–186.

Maya, L. F., Ruiz, M., Muttoni, A., & Foster, S. J. (2012). Punching shear strength of steel fiber reinforced concrete slabs. *Engineering Structures*, 40, 83–94.

The following website provides insight on the FHWA UHPC research portfolio: <http://www.fhwa.dot.gov/research/resources/uhpc/>



Breakthrough Concepts in Materials Science

PROJECT: Performance of Geosynthetic-Reinforced Soils at the Service Limit State

ASSOCIATE: Danial Esmaili

SCHOOL: University of Oklahoma

PERIOD: December 2014–October 2015

OBJECTIVE: To analyze large-scale performance test results to evaluate the effect of tensile strength, vertical reinforcement spacing, facing elements, and backfill properties on deformations of geosynthetic-reinforced soil under typical bridge support service pressures.

ADVISER: Jennifer E. Nicks, FHWA Office of Infrastructure Research and Development

SUMMARY: Geosynthetic-reinforced soil (GRS) technology consists of closely spaced layers of geosynthetic reinforcement and compacted granular fill material. This method of using geosynthetics to reinforce foundations is a proven alternative to the construction of deep foundations, depending on the site conditions. GRS is widely used for a variety of earthwork projects, particularly in GRS-integrated bridge system (IBS) applications. GRS-IBSs are economical and easy to design; they can be built in a variety of weather conditions and can be modified to accommodate characteristics of varying site conditions. An important geotechnical feature of any bridge foundation, including GRS bridge elements, is the service limit state (SLS), which ensures the durability and serviceability of a bridge and its structural components under everyday loads for the design life.

The SLS for GRS abutments primarily includes vertical settlement, lateral deformation, and reinforcement strain. Notwithstanding their widespread use in construction, the SLSs of GRS abutments have not been well defined.

Danial Esmaili's research project involved analyzing the results of a series of 13 large-scale column experiments (also called performance tests or minipier tests) conducted to help quantify both the SLS and ultimate limit state for GRS. The experiments were conducted on GRS piers consisting of different backfill materials, geosynthetic reinforcement strengths, and reinforcement spacing (the thickness of backfill between reinforcement layers). Some test piers were constructed with concrete masonry facing; others had no facing. All GRS

configurations were tested to failure, with the focus of this study on the performance at loads of 200 kPa (recommended allowable GRS bearing pressure) and 400 kPa (to test performance at extreme service loading). Key research findings of these experiments are that:

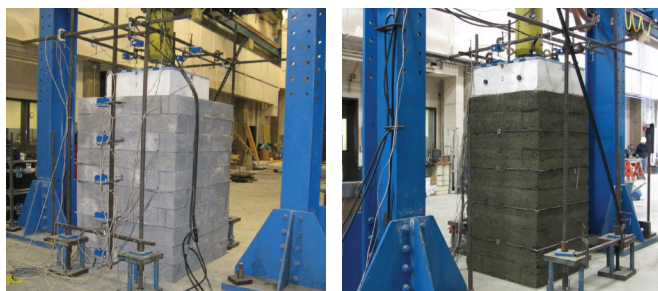
- GRS piers built with higher strength backfill undergo less lateral and vertical deformation.
- Settlement and lateral displacement at 200 kPa, depending on composition of test columns, ranged from 8.3 mm to 33.9 mm and 3.0 mm to 10.1 mm, respectively.
- Reinforcement spacing plays a larger role than does reinforcement strength in lateral and vertical deformation.
- Lateral movement of pier walls is greatest in the top third of the composite.
- Limiting-bearing pressure to 10 percent of the estimated bearing resistance of the GRS abutment will limit axial strains to within 0.5 percent of the abutment.

IMPACT: Data gathered through these experiments will help engineers more reliably design GRS-IBS projects without having to conduct complex and expensive laboratory testing.

RESOURCES: Several publications and papers resulted from this RAP research. They are outlined below.

Nicks, J. E., Esmaili, D., & Adams, M. T. (2016). Deformations of geosynthetic reinforced soil under bridge service loads. *Geotextiles and Geomembranes*, 44(4), 641–653.

Adams, M. T., Ooi, P. S. K., & Nicks, J. E. (2014). Mini-pier testing to estimate performance of full-scale geosynthetic reinforced soil bridge abutments. *Geotechnical Testing Journal*, 37(5).



Minipier tests helped quantify SLS for GRS with (left photo) and without (right photo) concrete masonry facing. Source: FHWA.



Breakthrough Concepts in Materials Science

PROJECT: Developing New Vehicle-Tire and Contact Friction Models

ASSOCIATE: Emmanuel Bolarinwa

SCHOOL: University of Birmingham

PERIOD: September 2013–September 2015

OBJECTIVE: To use a model-based approach for investigating the effect of tire-pavement contact friction on the safety performance of vehicles.

ADVISER: James A. Sherwood, FHWA Office of Infrastructure Research and Development

SUMMARY: The effective management of critical pavement surface characteristics, such as friction and texture, has been shown to help prevent or reduce the consequences of rear-end and run-off-the-road crashes. Although high-friction surfaces can lead to increased numbers of dry pavement rollovers, they also lead to fewer wet pavement run-off-the-road crashes and tend to have fewer crashes involving fatalities and serious injuries. For his research project, Emmanuel Bolarinwa implemented a model-based approach to investigate the effect of variations in vehicle- and tire-pavement friction on vehicle safety performance, such as stopping distances during braking. He considered the interactions among key crash causative factors and predicted vehicle performance and stability metrics. Bolarinwa examined a vehicle simulation package containing various values for pavement friction and texture inputs. For model verification, Bolarinwa obtained vehicle data and crash information from the Highway Safety Information System (HSIS) and the second Strategic Highway Research Program's naturalistic driving study. He then used the model to develop theoretical thresholds for pavement friction and texture inputs (i.e., the minimum values when crash rates have been found to increase at a significantly higher rate). Bolarinwa analyzed results from the simulation to extract vehicle performance and safety metrics as possible indicators of the onset of vehicle crashes for different vehicle types and a variety of road sections and geometries.

IMPACT: This research should lead to enhanced road safety, ensuring significant savings in cost and human lives by managing pavement friction. The research directly contributes to FHWA's strategic safety improvement program by predicting friction threshold values to determine conditions when a pavement should be investigated for maintenance intervention. Bolarinwa's research will lead to better characterization of the effects of a broad range of human, vehicle, and environmental factors on crash outcomes. It will also provide a basis for evaluating practices related to pavement surface material parameters and roadway geometry. FHWA will ultimately use the results of this research to develop new vehicle crash models, which will be of value to safety engineers working on State highway safety improvement programs. In addition, the results could be used to change pavement design standards to select the best pavements in terms of safety.

ONGOING RESEARCH: Bolarinwa continues research into the development of theoretical threshold values for pavement friction and development of procedures for predicting stopping distances based on the friction of the pavement surface. The long-term goal is to reduce fatal and severe (incapacitating injury) crashes, by prescribing levels of pavement friction and macrotexture.



A simulation model for investigating vehicle behavior on a sloped terrain surface. Source: FHWA.



Breakthrough Concepts in Materials Science

RESOURCES: Several publications and papers resulted from this RAP research. They are outlined below.

Uzunsoy, E., Bolarinwa, E., Olatunbosun, O., & He, R. (2014). *Investigating vehicle behavior on a sloped terrain surface*. SAE Technical Paper 2014-01-0857.

Yang, X., Olatunbosun, O., Ramos, D. G. P., & Bolarinwa, E. (2013). Experimental investigation of tire dynamic strain characteristics for developing strain-based intelligent tire system. *SAE International Journal of Passenger Cars-Mechanical Systems*, 6(1), 97-108.

Bolarinwa, E. O., Mahadevaiah, U., Marzougui, D., & Opiela, K. S. (2012). The development of an enhanced finite element tire model for roadside safety hardware assessment. *Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multi-Body Dynamics*, 226(3), 206-219.

Bolarinwa, E. O. (2014). *Material and geometrical characterization for FE tire modeling and simulation*. Paper presented at the 2014 Tire Technology Expo Conference, Cologne, Germany.

Bolarinwa, E. O. (2013). *Development of an FE tire model for vehicle crash simulations*. Paper presented at the 2013 Tire Technology Expo Conference, Cologne, Germany.

Bolarinwa, E. O. (2013). *Experimental investigation of vehicle behavior on a sloped-terrain surface*. Paper presented during the SAE 2013 World Congress and Exhibition, Detroit, MI.

Bolarinwa, E. O. (2012). *Role of tire testing in efforts to develop improved finite element models to support crash simulation*. Workshop on Improving the Modeling of Tire, Steering and Suspension Systems in Angular Crashes, FHWA Turner-Fairbank Highway Research Center, McLean, VA.

Bolarinwa, E. O. (2011). *The development of an enhanced finite element tire model for vehicle crash simulations*. Paper presented at the 30th Annual Conference on Tire Science and Technology, Akron, OH.

Bolarinwa, E. O. (2011). *Role of tire testing in efforts to develop improved finite element vehicle models to support crash simulations*. Paper presented at the 2011 Tire Technology Expo Conference, Cologne, Germany.



Breakthrough Concepts in Materials Science

PROJECT: Use of Inorganic Coatings as Curing Compounds

ASSOCIATE: Jessica Silva

SCHOOL: University of Wisconsin–Madison

PERIOD: September 2012–December 2013

OBJECTIVE: To develop inorganic curing compounds to address the shortcomings of current organic membrane-forming curing compounds.

ADVISER: Jack S. Youtcheff, FHWA Office of Infrastructure Research and Development

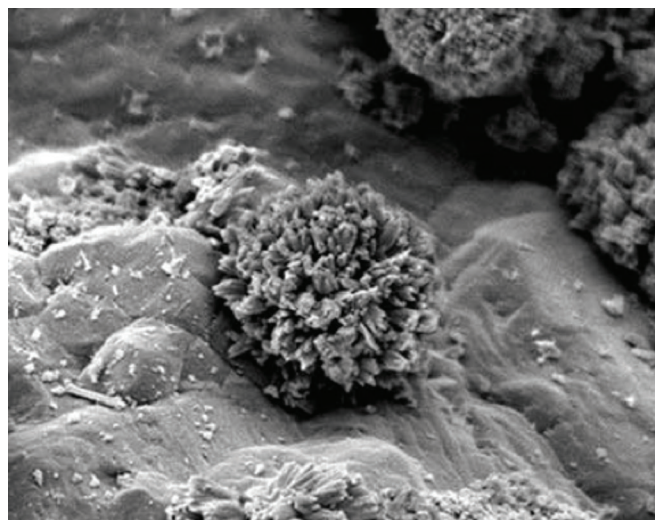
SUMMARY: Proper curing is a vital post-treatment process when constructing durable concrete pavements. This is because water loss by evaporation through exposed surfaces can result in mechanical or chemical deficiencies in the final surface of the concrete product. Existing membrane-forming curing compounds are widely used to form a physical barrier to prevent the migration of water during the first few hours of concrete placement; however, these membranes do not always form a continuous coating, may degrade after environmental exposure, and provide little protection of the concrete section at later stages of the pavement's service life. Jessica Silva's research project examined the use of inorganic curing compounds to address the shortcomings of current organic compounds. These inorganic curing compounds, prepared from metal-oxide materials, can react with the concrete surface to form durable coatings and hydration products. The compounds may also impart beneficial characteristics to the roadway and provide improvements to the pavement long after traditional membranes. Silva examined changes occurring to the air and mortar and mortar and aggregate interface, in addition to the porosity, density, and chemical makeup of the cement paste. Silva also ensured that the inorganic curing compounds under development would not adversely affect the concrete material. As part of this research project, Silva used a traceable element to better understand the effect of the compound as it penetrates the concrete.

IMPACT: This research could represent a paradigm shift in the world of curing compounds. In addition, if the material developed as a result of this research is not ultimately useful as a curing compound, it may still prove useful to enhance general concrete characteristics.

RESOURCES: Several publications and papers resulted from this RAP research. They are outlined below.

Silva, J. M. S., Youtcheff, J., & Arnold, T. (2013). Utilizing sol-gel nanoparticles in concrete curing to improve surfaces. *National Research Council Research Associateship Programs Newsletter*, 14–16.

Munoz, J. F., Silva, J. M. S., Perry, L., Youtcheff, Y., & Sobolev, K. (2014). Interaction of amorphous nano-aluminosilicates with cement pore solution and the effect on the early hydration reaction of portland cement. *Proceedings of the Fifth International Symposium on Nanotechnology in Construction*.



Nucleation of ettringite mineral in the interfacial transition zone.
Source: FHWA.



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–April 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 Research and Development

SUMMARY: Jose Muñoz examined a method to enhance the area of contact between cement-paste aggregates and asphalt aggregates, known as the *interfacial region*. This is one of the most vulnerable areas of concrete and asphalt, potentially affecting the overall performance of pavement. The durability of concrete is highly influenced by its pore structure, specifically a highly porous area known as the *interfacial transition zone* (ITZ). Large fractions of the microcracks occurring in concrete are associated with the ITZ; therefore, improving the strength of the ITZ could significantly improve concrete durability. Traditional approaches to the problem, involving the successive addition of different silicon or aluminum-based materials, have been inefficient and costly. Muñoz based his research on the theory that nanoparticles added as nanoporous films, and when judiciously placed on the aggregate surface, can greatly improve the ITZ and thereby the performance of the concrete. He investigated changes triggered by nanoporous thin films in the chemistry and morphology of the hydration products located at the aggregate–cement–paste interface. Muñoz developed a model to determine two-dimensional spatial distribution of cement hydration phases and to study the aggregate–cement–paste interface in concrete. In addition, Muñoz developed a new sol-gel synthesis (a method for producing solid materials from small molecules) to produce “nano-aluminosilicate” gels with a controlled silicon-to-aluminum ratio. Muñoz also studied the effect of these nano-aluminosilicate gels with different silicon-to-aluminum ratios on the hydration reaction of portland cement.

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. The application of nanoparticles in concrete and asphalt, using dip- or spray-coating methods, offers several advantages when compared with the traditional addition of nanoparticles as powder additives. It is an easier and safer application method—fewer additives are required, which reduces costs—and the technology is already available. In addition, this technology can have

a positive impact in locations with limited or marginal-quality aggregate sources. For example, these nano-additives can be used to improve performance of currently marginal aggregates, such as natural aggregate with significant contents of clay minerals strongly adhered to their surface.

ONGOING RESEARCH: Muñoz continues to study the effect of the nanoparticles in concrete pore solution at early stages of hydration. In addition, he also performed research with the U.S. Army Engineer Research and Development Center to characterize the ITZ modified with nanoparticles.

RESOURCES: Several publications and papers resulted from this RAP research. They are outlined below.

- Muñoz, J. F., Meiningner, R. C., & Youtcheff, J. (2010). New possibilities and future pathways of nanoporous thin film technology to improve concrete performance. *Transportation Research Record, Journal of the Transportation Research Board*, 2142, 34–41.
- Muñoz, J. F., Yao, Y., Youtcheff, J., & Arnold, T. (2011). Nanotechnology to improve aggregate performance. *National Research Council, Research Associateship Program Newsletter*.
- Muñoz, J. F., Yao, Y., Arnold, T., & Youtcheff, J. (2013). Mixtures of silicon and aluminum oxides to optimize the performance of nanoporous thin films in concrete. *Cement and Concrete Composites*, 48.
- Munoz, J. F., Silva, J. M. S., Perry, L., Youtcheff, Y., & Sobolev, K. (2014). Interaction of amorphous nano-aluminosilicates with cement pore solution and the effect on the early hydration reaction of Portland cement. Proceedings of the *Fifth International Symposium on Nanotechnology in Construction*.
- Balachandran, C., Muñoz, J. F., Arnold, T., & Youtcheff, J. (2014). Potential application of surface enhanced Raman spectroscopy as a tool to study cementitious materials. Proceedings of the *Fifth International Symposium on Nanotechnology in Construction*.



Connected Highway and Vehicle System Concepts

PROJECT:	Design and Implementation of an MPC-Based Framework for Vehicle Platooning
ASSOCIATE:	Mohammad Goli
SCHOOL:	The George Washington University
PERIOD:	January 2019–October 2020
OBJECTIVE:	To develop the cooperative automated vehicle control and the vehicle platooning framework for a cooperation-enabled ADS to support CARMA.
ADVISER:	Taylor William Paul Lochrane , FHWA Office of Operation Research and Development

SUMMARY: Mohammad Goli's research work involved several areas:

- Vehicle localization using EKF: Vehicle localization is the science of estimating the position and orientation of cars in a predefined frame using one or more sensors such as GPS, IMU, LiDAR, and radar. To this end, he and his colleagues chose to implement the EKF algorithm, which is a technique dealing with uncertain information coming from the measurement system and a model that describes the motion of the vehicle at each time step, again with a degree of uncertainty, to estimate the pose of the vehicle. He and his colleagues were able to simulate an EKF algorithm that brings in information from sensors such as GPS and IMU and combines it with the information coming from the motion model to estimate the vehicle's position with respect to a predefined inertial frame.
- Platooning framework and platooning process design: A platooning framework is intended to provide an understanding of how different levels of task decisions are structured for vehicle platooning. Goli and his colleagues proposed a structure that organizes different activities into two layers called the mission layer and the behavior layer. In each layer, different modules are defined to formalize the decision-making process by assigning different decisions to different modules. The overall goal of all modules in the two proposed layers is to break down the driving task in a platoon into different subtasks that can be encoded into finite state machines.
- Mission layer: The mission layer has two modules named journey manager and destination manager. The goal of the mission layer is to make high-level decisions regarding the sequence of major destinations as well as the sequence of route segments.
- Behavior layer: The behavior layer includes three different modules, which are mainly concerned with the factors that affect the autonomous driving behavior of each vehicle in the platoon:
 - Route segment manager.
 - Driving behavior planner.
 - Maneuver planner.
- Platooning process design: In this part of Goli's work, he and his colleagues aimed at proposing a high-level platooning process design which describes how an individual vehicle would request to join a platoon, initiate the matching process, negotiate formation, follow in the platoon (i.e., maintain the platoon), and eventually dissolve or leave the platoon.
- CARMA 11th initiative :The goal of the CARMA 11th project is to enable the development and testing of CARMA features on a much lower-cost, scaled down robotic platform so that a much larger research community could get involved in the CARMA developments without compromising or limiting the functionality of any aspects of it. Goli worked with others to build and test three scaled-down vehicles at TFHRC. The vehicles are equipped with computing boards, a LiDAR , a stereo camera, IMU, and some other devices to facilitate ADS and cooperative driving automation testing.



Connected Highway and Vehicle System Concepts

PROJECT: Toward Safer and Efficient Implementation of Automated Driving Systems: Performance Measurements and Evaluation

ASSOCIATE: Mohamed Ahmed

SCHOOL: University of Wisconsin-Milwaukee

PERIOD: September 2019–September 2020

OBJECTIVE: To improve safety and operation research in ADS.

ADVISER: Shyuan-Ren (Clayton) Chen, FHWA Office of Safety Research and Development

SUMMARY: Highly automated vehicles (AV) have been progressively tested on public roads for many years; however, there is no subjective and systematic way to evaluate their safety. Due to the proprietary nature of AV manufacturers, trajectory-level crash and near-crash precursors data are missing. Transportation agencies will need to find a mechanism to acquire or substitute such data.

Mohamed Ahmed's research work investigated five methodologies that have been proposed as potential methods to assess the safety of ADS, including field testing, microsimulation, driving simulators, hardware-software-in-the-loop simulation, and naturalistic driving studies.

He found that preliminary research, literature review, and interaction with various stakeholders have shown that all these approaches are needed, and they complement one another. According to Ahmed, a new naturalistic driving study is needed to assess commercially available level 1 and 2 AVs, which could be extended to level 3 as some AV manufacturers are claiming to have it in the near future.

RESOURCES: Several publications resulted from this RAP research. They are outlined below.

Khoda, A., A. Gaweesh, and M. Ahmed. 2021. "The Safety Performance of Connected Vehicles on Slippery Horizontal Curves through Enhancing Truck Drivers' Situational Awareness: A Driving Simulator Experiment." *Transportation Research Part F: Traffic Psychology and Behaviour* 79, no. 2: 118–138.

Khan, N., M. Ahmed. 2021. "Weather and Surface Condition Detection Using Road-Side Webcams: Application of Pre-trained Convolutional Neural Network." *International Journal of Transportation Science and Technology*. <https://doi.org/10.1016/j.ijtst.2021.06.003>.

Khan, N., M. Ahmed. 2021. "WeatherNet: Development of a Novel Convolutional Neural Network Architecture for Trajectory-Level Weather Detection Using SHRP2 Naturalistic Driving Data." *Transportation Research Record: Journal of the Transportation Research Board* 2675, no. 9: 1016–1030.

Ahmed, I., and M. Ahmed. 2021. "Injury Severity Analysis of Adverse Vs. Non-Adverse Weather Condition Crashes in Rural Two-Lane Two-Way Highways—A Random Intercept Bayesian Approach." Presented at the 100th Annual Meeting of the Transportation Research Board. Washington DC: Transportation Research Board.



Connected Highway and Vehicle System Concepts

PROJECT: Implement Hardware-in-the-loop in More Complex and Realistic Way with Artificial Intelligence

ASSOCIATE: Yu Cui

SCHOOL: University of Buffalo

PERIOD: April 2019–March 2020

OBJECTIVE: TTo investigate AI methodology related to hardware-in-the-loop.

ADVISER: Peter Huang, FHWA Office of Operations Research and Development

SUMMARY: Yu Cui worked on using loop signatures extracted from inductance loop detectors. Yu Cui also employed artificial intelligent methodologies to match loop signatures from an identical vehicle.

Yu Cui conducted a literature review about artificial intelligent methodologies in traffic signal timing optimization area. The methods are mainly focused on fuzzy logic, deep learning, and reinforcement learning.

PROJECT: Initiation of an Effective Highway Performance Management Strategy by Integrating Multiple Transportation Data Sets

ASSOCIATE: Zhuo Yang

SCHOOL: George Mason University

PERIOD: January 2019–December 2019

ADVISER: Tianjia Tang, FHWA Office of Office of Highway Policy Information

SUMMARY: During his RAP tenure, Zhuo Yang accomplished the following:

- Conducted a highway performance study based on the national performance management research data set.
- Conducted a traffic pattern identification study based on the travel monitoring analysis system data.



Connected Highway and Vehicle System Concepts

PROJECT: Developing Automated Driving Systems and Predicting Highway Wide Impacts

ASSOCIATE: Pavle Bujanovic

SCHOOL: The University of Texas at Austin

PERIOD: August 2018–August 2019

OBJECTIVE: To develop and advance current vehicle platooning concepts on CARMASM and using simulation tools to predict the impact of cooperation-enabled automated driving systems (ADS) on highways.

ADVISER: Taylor William Paul Lochrane, FHWA Office of Operation Research and Development

SUMMARY: Pavle Bujanovic worked on four main areas:

- Localization solution.
- Platooning framework.
- Lane detection algorithm.
- Global Positioning System (GPS) signal limitations.

In localization, the purpose is to find a subdecimeter-level location to allow a vehicle to know almost exactly where it is, which is especially important with connected vehicles (CVs). CVs rely on receiving accurate information from other vehicles in order to determine how to execute their own upcoming maneuvers with the most efficiency; to implement a localization solution, Bujanovic and his colleagues used an Extended Kalman Filter (EKF) that updates beliefs about where the vehicle thinks it is based on a dynamic motion model with current sensor readings. In simulation, he implemented an EKF that used a radar and light detection and ranging (LiDAR) to identify the location of other vehicles with respect to the subject vehicle. Bujanovic and his colleagues began using GPS, inertial measurement unit (IMU), and odometry sensors to help a subject vehicle locate itself with respect to a fixed map frame.

In addition, he worked on developing a platooning framework. The framework is divided into different layers, each of which is responsible for helping a platoon move from origin to destination. The mission layer is the uppermost layer, and it exists to allow vehicles to determine if they should get together to form a platoon based on their destinations, and if so, where and when they should join and later split. Within the mission layer are the behavior planning and maneuvers planning layers. These layers allow the platoon to decide what behavior it needs to execute (e.g., pass a slow vehicle in front), what maneuvers make up that behavior, and how these maneuvers should be executed. In his work with vehicle cameras, he also developed a lane detection algorithm. The algorithm works by processing each frame and applying various filters, such as the Sobel filter, to detect lane lines and then determining how the vehicle needs to move in order to be in the middle of the lane. The algorithm has been tested successfully on video captured in typical driving conditions and will continue to undergo further tests and development for more complex scenarios. Lastly, he spent time studying GPS signals. He helped discover several different issues that limit or obstruct GPS signals when equipment is installed on vehicles. For example, loose cables or exposed cables/wires from other equipment can interfere with the GPS signal, causing the GPS antennas to completely miss it.

RESOURCES: Khoda, A., and M. Ahmed. 2021. "A Note on Random Forest Visualization Tools in Post-Hoc Interpretation of Nonparametric Real-Time Risk Assessment Models." Presented at the 100th Annual Meeting of the Transportation Research Board. Washington DC: Transportation Research Board.



Connected Highway and Vehicle System Concepts

PROJECT: Cost-Benefit Analysis of Connected and Automated Vehicle Operations

ASSOCIATE: Mehdi Zamanipour

SCHOOL: University of Arizona

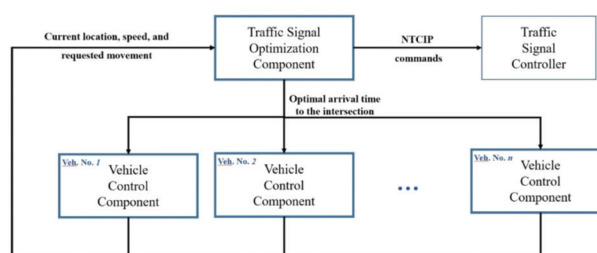
PERIOD: September 2016–November 2019

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 these systems.

ADVISER: Govindarajan Vadakpat, FHWA Office of Safety Research and Development

SUMMARY: Mehdi Zamanipour evaluated the costs and benefits of deploying CAV technologies along signalized traffic corridors. His research examined two specific wireless communications applications—Multi-Modal Intelligent Traffic Signal Systems (MMITSS) and GlidePath. Developed under U.S. Department of Transportation (USDOT) programs, both systems get technologically advanced vehicles “talking” to each other and to computerized roadside infrastructure. MMITSS uses the data generated in such communications to optimize the movements of transit and freight traffic, emergency vehicles, and pedestrians, while GlidePath is designed to maximize fuel efficiency as vehicles move through traffic signals. Zamanipour developed a simulation environment for analyzing these technologies. The elements of the simulator include the CAV Message Distributor application, containerization technology to run MMITSS and GlidePath, and traffic flow software. This package collects information from CAVs, broadcasts messages to roadside infrastructure, sets an emission model, and controls driving behaviors like speed and acceleration for each vehicle. Zamanipour used the USDOT-sponsored Research Data Exchange to calibrate baseline software models for traffic demand and signal time based on U.S. Environmental Protection Agency guidelines.

IMPACT: Although the simulation environment in this project was created to analyze MMITSS 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.



The proposed integrated signal and trajectory control optimization framework.
© Mehdi Zamanipour.

RESOURCES: Several publications and papers resulted from this RAP research. They are outlined below.

- Beak, B., Zamanipour, M., Head, L., & Leonard, B. (2018). Peer-to-peer priority signal control strategy in a connected vehicle environment. *Transportation Research Record: Journal of the Transportation Research Board*. Available online: <https://doi.org/10.1177/0361198118773567>.
- Zamanipour, M., Head, K. L., Feng, Y., & Khoshmagham, S. (2016). Efficient priority control model for multimodal traffic signals. *Transportation Research Record: Journal of the Transportation Research Board*, 2557, 86–99. Available online: <http://dx.doi.org/10.3141/2557-09>.
- Feng, Y., Zamanipour, M., Head, K. L., & Khoshmagham, S. (2016). Connected vehicle-based adaptive signal control and applications. *Transportation Research Record: Journal of the Transportation Research Board*, 2558, 1–13. Available online: <http://dx.doi.org/10.3141/2558-02>.
- Khoshmagham, S., Head, K. L., Feng, Y., & Zamanipour, M. (2016). Multimodal data analytics comparative visualization tool: Case study of pedestrian crossing design. *Transportation Research Record: Journal of the Transportation Research Board*, 2557, 44–54. Available online: <http://dx.doi.org/10.3141/2557-05>.
- Feng, Y., Head, L., Khoshmagham, S., & Zamanipour, M. (2015). A real-time adaptive signal phase allocation algorithm in a connected vehicle environment. *Transportation Research Part C: Emerging Technologies*, 55, 460–473.
- Zamanipour, M., Hu, J., Vadakpat, G., Bared, J., & Curtis, D. (2018). *A design of cooperation between traffic signal and connected automated vehicle*. Presented at the 97th Transportation Research Board Annual Meeting, Washington, DC.
- Beak, B., Zamanipour, M., Head, L., & Leonard, B. (2018). *Peer-to-peer priority signal control strategy in connected vehicle environment*. Presented at the 97th Transportation Research Board Annual Meeting, Washington, DC.



Connected Highway and Vehicle System Concepts

PROJECT: Knowledge-Based Signal Timing and Optimization Expert System for Advanced Urban Signal Control

ASSOCIATE: Yi Zhao

SCHOOL: Beijing Jiaotong University

PERIOD: December 2015–June 2018

OBJECTIVE: To develop a knowledge-based signal timing and optimization expert system and employ a robust evaluation methodology to test its applicability.

ADVISER: Peter Huang, FHWA Office of Safety Research and Development

SUMMARY: The limitations of adaptive traffic control systems as a tool to optimize signal timing posed an opportunity for Yi Zhao to develop a knowledge-based expert system to improve existing signal-control systems. Knowledge-based expert systems are an artificial intelligence (AI) technique to help people analyze and solve problems. Zhao also applied artificial neural network technology for traffic-demand prediction.

His project consisted of five major tasks:

- Designing a system framework.
- Developing a hybrid origin–destination (OD) model to estimate traffic demand.
- Developing a system to generate plans and select the appropriate options from the plans, based on real-time traffic data.
- Optimizing the signal timing plan by using this system.

For his hybrid OD estimation model, Zhao integrated different types of traffic data (time of day, day of week, and average daily traffic count), pulling data from various sources (wireless traffic sensors, link-based traffic sensors, and national survey data). He used AI to estimate each small-area OD, which can be used to generate any size of scalable ODs to support advanced signal operations. A unique feature of Zhao's work is assembling an OD table from many small-area ODs, which is just like assembling a puzzle from small pieces. In this way, a scalable OD can be made to provide much improved, timely demand data for more effective signal timing.

IMPACT: Traffic engineers will benefit from Zhao's research as they work to improve the efficiency of U.S. traffic signals. The software package he developed will help them optimize signal timing practices based on AI technology. This advanced system is working on the basis of more accurate traffic-demand data, and it can become "smarter over time" on the basis of accumulated knowledge in the expert system and machine-learning technique.

RESOURCES: One publication and several papers resulted from this RAP research. They are outlined below.

Zhao, Y., James, R., Xiao, L., & Bared, J. (2018). A capacity estimation model for a contraflow left-turn pocket lane at signalized intersections. *Transportation Research Record: Journal of the Transportation Research Board*. Available online: <http://journals.sagepub.com/doi/10.1177/0361198118787978>.

Zhao, Y., Huang, P., Xiao, L., Ma, J., Hu, J., & Wang, Y. (2017). *A scalable short-term origin-destination estimation approach based on modularized network with connected vehicle technology*. Presented at the 96th Transportation Research Board Annual Meeting, Washington, DC.

Wolfram, J., Huang, P., Zhao, Y., & Christofa, E. (2018). *A quick and reliable traffic incident detection methodology using connected vehicle data*. Presented at the 97th Transportation Research Board Annual Meeting, Washington, DC.

Wang, Y., Zhao, Y., Zhang, W., Bared, J., & Huang, P. (2017). Signal timing strategies for Georgia's first in-house designed DDI, 5th Urban Street Symposium, Raleigh, NC.

Xiao, L., Wang, Y., Hu, J., & Zhao, Y. (2017). *Responsive signal control with active connected vehicles*. Presented at the 96th Transportation Research Board Annual Meeting, Washington, DC.

Zhao, Y., James, R., Xiao, L., & Bared, J. (2018). *A capacity estimation model for a contraflow left-turn lane at signalized intersections*. Presented at the 97th Transportation Research Board Annual Meeting, Washington, DC.

Wang, Y., Zhao, Y., Zhang, W., Bared, J., & Huang, P. (2017). *Signal timing strategies for Georgia's first in-house designed DDI*. Presented at the 5th Urban Street Symposium, Raleigh, NC.

Zhao, Y., James, R., Xiao, L., & Bared, J. (2017). *A capacity estimation model for a contraflow left-turn lane at signalized intersections*. Presented at the 5th Urban Street Symposium, Raleigh, NC.



Connected Highway and Vehicle System Concepts

PROJECT: Development of an Eco-Cooperative Adaptive Cruise Control to Optimize Vehicle Performance for Environment and Mobility Benefits

ASSOCIATE: Jia Hu

SCHOOL: University of Virginia

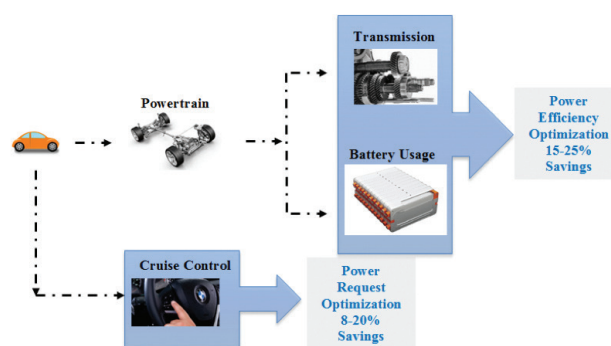
PERIOD: October 2014–July 2017

OBJECTIVE: To develop an algorithm for eco-cooperative adaptive cruise control (ECACC) that accounts for road topography to minimize fuel consumption and emissions while maximizing mobility.

ADVISER: Joe Bared, FHWA Office of Operations Research and Development

SUMMARY: Eco-driving systems improve fuel efficiency by keeping equipped vehicles within a range of speeds in mountainous terrain rather than at a fixed speed like conventional cruise control. However, the algorithms that these systems use do not gauge their impact on mobility. Jia Hu sought to develop a framework for ECACC that could minimize a vehicle's fuel consumption while maximizing its mobility. His research also evaluated how speed changes within the ECACC framework could affect vehicle safety performance. Hu reviewed literature on three topics—state-of-the-art ECACC, fuel consumption models that consider variables like vehicle speed and roadway grade, and car-following models. In the next phase of work, he developed an algorithm for ECACC in three stages. Using simulation tools, Hu initially designed the algorithm to optimize both fuel economy and mobility for a single vehicle. Next, he expanded the algorithm to traffic scenarios that mixed one ECACC-equipped vehicle with human-driven vehicles. The third phase of algorithm development envisioned multiple vehicles using ECACC. Hu finished the project by testing the algorithm and evaluating the results. To complete this testing, Hu had to identify several stretches of highways with different topographies to serve as the prototype for a simulation test bed. The tests considered average grade and grade changes in the road, vehicle weight, target speed range, and other factors when gauging the performance of the algorithm. Hu compared the fuel efficiency, emissions, speed, vehicle spacing, throughput, and number of conflicts that occurred in multiple ECACC simulations.

IMPACT: Hu's project is expected to generate an ECACC framework that can maximize fuel efficiency and minimize the technology's impact on mobility, regardless of the road topography the vehicle is traveling. The framework should work for either a lone ECACC-equipped vehicle or a platoon of them. As a secondary benefit, the research could demonstrate improved safety performance for vehicles with ECACC.



Hu's research shows that an eco-CACC with a connected powertrain can bring additional fuel savings of 15 to 25 percent, compared with mere speed optimization. © Jia Hu

RESOURCES: Several publications and papers resulted from this RAP research. They are outlined below.

- Hu, J., Shao, Y., Sun, Z., & Bared, J. (2017). Integrated vehicle and powertrain optimization for passenger vehicles with vehicle-infrastructure communication. *Transportation Research Part C: Emerging Technologies*, 79, 85–102.
- Jiang, H., Hu, J., An, S., Wang, M., & Park, B. B. (2017). Eco approach at an isolated signalized intersection under partially connected and automated vehicle environment. *Transportation Research Part C: Emerging Technologies*, 79, 290–307.
- Zhang, L., Zhang, L., Hale, D., Hu, J., & Huang, Z. (2017). A cycle-based variable speed limit methodology for improved freeway merging. *IET Intelligent Transport Systems*, 11, DOI: 10.1049/iet-its.2017.0017.
- Hu, J., Shao, Y., Sun, Z., Wang, M., Bared, J., & Huang, P. (2016). Integrated optimal eco-driving on rolling terrain for hybrid electric vehicle with vehicle-infrastructure communication. *Transportation Research Part C: Emerging Technologies*, 68, 228–244.
- Ma, J., Hu, J., Hale, D., & Bared, J. (2016). Dynamic hard shoulder running for traffic incident management. *Transportation Research Record: Journal of the Transportation Research Board*, 2554, 120–128.



PROJECT: Developing and Implementing Dynamic Junction Control System in the United States

ASSOCIATE: Ximiao Jiang

SCHOOL: University of Tennessee, Knoxville

PERIOD: October 2013–May 2015

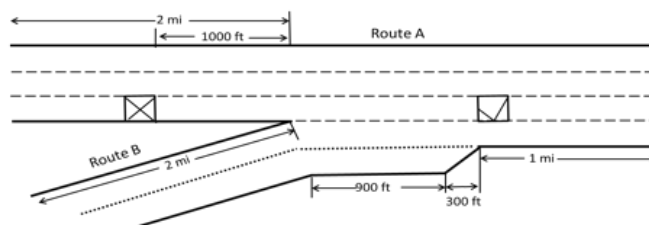
OBJECTIVE: To investigate the efficiency of dynamic merge control (DMC) strategy at freeway merge areas.

ADVISER: Joe Bared, FHWA Office of Operations Research and Development

SUMMARY: DMC is a traffic management strategy that can be used to dynamically monitor and control traffic flow at freeway on- or off-ramps or where multiple-lane freeways merge—for example, where a 2-lane freeway merges with a 3-lane freeway into 4 lanes. DMC minimizes disruption that can occur, for example, when traffic volume on an on-ramp is significantly higher than on the freeway. In this case, ramp traffic must find gaps in lower volume freeway traffic, resulting in hesitation and delay and increasing the possibility of rear-end collisions. DMC strategy, now being used in Germany and the Netherlands, assigns priority to the high-volume traffic stream. In the example above, DMC could close the right lane of the main freeway and allow ramp traffic free access at the merge. DMC has not been implemented anywhere in the United States, and knowledge of the strategy is still experimental here.

Ximiao Jiang's research project used an analytical technique called microsimulation to examine the effectiveness of DMC on several road and traffic configurations. Microsimulation can effectively model the behavior of many individual vehicles within specified traffic environments, including merge queuing and congested road networks, to the point of gridlock. Jiang simulated DMC lane-closing strategy on two traffic configurations: the first, two 2-lane freeways merging into 3 lanes, and the second, a 3-lane freeway merging with a 2-lane freeway into 4 lanes. Simulations included traffic demands ranging from 1,000 vehicles per hour (vph) to 4,600 vph on 3 lanes and 2,500 vph to 6,500 vph on 2 lanes. In the simulations, signals notify drivers of lane closure 2,500 ft upstream of the lane closing and close the lane 1,000 ft upstream of the merge. The simulation assumed that drivers would be 100-percent compliant with lane closure. Fifteen runs were simulated for each scenario. Key findings of the simulations are:

- Implementing DMC strategy produced benefits in vehicle delay and speed at almost all demand combinations.
- When traffic demand on the minor roadway reached 1,900 vph per lane, DMC benefits became statistically and practically significant.
- DMC reduced lane changing in the merge area, thereby increasing capacity and delaying the formation of bottlenecks.



Microsimulation studies evaluated dynamic merge control in configurations such as a 2-lane freeway merging with a 3-lane freeway to form four traffic lanes.

From Jiang, X., J. Bared, M. Maness, and D. Hale. Traffic Performance Analysis of Dynamic Merge Control Using Microsimulation. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2484, Figure 1, p. 24, 2015. Reproduced with permission of the Transportation Research Board.

IMPACT: This research represents an important first step in evaluating the DMC strategy as an effective approach to reducing delays and congestion at freeway merge areas.

ONGOING RESEARCH: The next phase of DMC microsimulation will investigate varying closing locations and varying distances at which drivers are warned. The next phase also will investigate various closed-lane compliance ratios.

RESOURCES: Several publications resulted from this RAP research. They are outlined below.

Jiang, X., Gan, Q., Bared, J., Mannes, M., & Hale, D. (2015). Traffic performance analysis of dynamic merge control using microsimulation. *Transportation Research Record, Journal of the Transportation Research Board*, 2484.

Zhang, Y., Jiang, X., Haghani, A., & Huang, B. (2015). Exploring nonlinear effects of traffic crash determinants using a novel poisson-mixed multivariate adaptive regression splines model. *Transportation Research Record, Journal of the Transportation Research Board*, 2515.



Human Behavior and Travel Choices

PROJECT: Using Naturalistic Driving Study Data to Analyze Behavior at Signalized Intersections

ASSOCIATE: Chenhui Liu

SCHOOL: Iowa State University

PERIOD: August 2018–October 2020

OBJECTIVE: Analyze behavior at signalized intersections with NDS data.

ADVISER: Wei Zhang, FHWA Office of Safety Research and Development

SUMMARY: Chenhui Liu's research involved sifting through and analyzing the raw SHRP 2 reduced intersection dataset from the Virginia Tech Transportation Institute. The dataset is invaluable for studying driver behaviors at intersections. However, due to the privacy issue and high costs, the dataset has been unavailable to most researchers until now. Liu's work lays a solid foundation for researchers to continue naturalistic driver behavior analysis in the future.

RESOURCES: Several publications and papers resulted from this RAP research. They are outlined below.

Yu, S., L. Wang, G. Wang, C. Liu, and L. Yang. 2020. "Estimation and Inference for Generalized Geoadditive Models." *Journal of the American Statistical Association* 115, no. 530: 761–774.

Zhao, S., K. Wang, C. Liu, and E. Jackson. 2019. "Investigating the Effects of Monthly Weather Variations on Freeway Crash Experience." *Journal of Safety Research* 71: 153–162.

Li, X., C. Liu, J. Jia. 2019. "Ownership and Usage Analysis of Alternative Fuel Vehicles in the United States with the 2017 National Household Travel Survey Data." *Sustainability* 11, no. 8: 2262–2277.

Liu, C., C. Lu, S. Wang, A. Sharma, and J. Shaw. 2019. "A Longitudinal Analysis of the Effectiveness of California's Ban on Cellphone Use While Driving." *Transportation Research Part A* 124: 456–467.

Liu, C., and A. Sharma. 2019. "Are You Going to Get A Ticket or A Warning for Speeding? An Autologistic Regression Analysis in Burlington, VT." *Transportation Research Interdisciplinary Perspectives* 1: 100001.

Lu, C., Dong, J., L. Hu, and C. Liu. 2019. "An Ecological Adaptive Cruise Control for Mixed Traffic and Its Stabilization Effect." *IEEE Access* 7, no.1: 81246–81256.

Zhang, W., C. Liu, and L. Xiao. 2019. "Predicting Vulnerable Road User Crashes Based on Seasonable Pattern." Presented at the International Conference on Transportation and Development. Alexandria, VA: American Society of Civil Engineers.



Human Behavior and Travel Choices

PROJECT: Driving the Highway Safety Manual to Perform Better: A Fourfold Research

ASSOCIATE: Seyedehsan Dadvar

SCHOOL: Morgan State University

PERIOD: June 2019–July 2020

OBJECTIVE: To improve tools for data-driven safety analysis.

ADVISER: Shyuan-Ren (Clayton) Chen, FHWA Office of Safety Research and Development

SUMMARY: Seyedehsan Dadvar participated in ongoing Geometric Design Lab activities, in particular testing and reviewing the Interactive Highway Safety Design Model development and support (e.g., IHSDM 2019 (version 15.0.0) and IHSDM 2020 (version 16.0)). Dadvar calibrated the severity distribution functions of the Highway Safety Manual (HSM) using data from Maryland for freeway segment model.

Dadvar conducted a literature catalog and review on “HSM”-related publications (830+ records), including an online summary table of the HSM Part C Crash Modification Factors (CMF) or Adjustment Factors (AF), “NDS”-related publications (2,300+ records), and AV (levels 2 and 3) owner manuals for active auto manufacturers (40+ records) and digitized and geocoded California Department of Motor Vehicle AV crash reports (2014–present: 259 crash reports).

RESOURCES: Several publications and papers resulted from this RAP research. They are outlined below.

Dadvar, S., Y.-J. Lee, and H.-S. Shin. 2020. “Improving Crash Predictability of the Highway Safety Manual through Optimizing Local Calibration Process” *Accident Analysis and Prevention* 136. <https://doi.org/10.1016/j.aap.2019.105393>.

Shin, H.-S., S. Dadvar, S. Bharti, and Y.-J. Lee. 2020. “Results and Lessons from Local Calibration Process of the Highway Safety Manual for the State of Maryland: Freeway Segments, Speed-Change Lanes, And Ramp Terminals.” *Journal of Transportation Safety and Security*. <https://doi.org/10.1080/19439962.2020.1786758>.



Human Behavior and Travel Choices

PROJECT: Effectiveness of High-Visibility Crosswalks in Improving Pedestrian Safety

ASSOCIATE: Tawfiq Sarwar

SCHOOL: State University of New York–University at Buffalo

PERIOD: November 2016–September 2018

OBJECTIVE: To analyze crashes and near-crashes using Strategic Highway Research Program 2 (SHRP 2) naturalistic driving study (NDS) data and evaluate the effectiveness of high-visibility crosswalks (HVCs) in improving pedestrian safety.

ADVISER: Carol Tan, FHWA Office of Safety Research and Development

SUMMARY: Tawfiq Sarwar’s exploration of HVCs as a potential tool to improve pedestrian safety is an extension of research conducted under SHRP 2. The researchers for the initial project analyzed video data of driver behavior that was collected in two SHRP 2 projects—NDS and the roadway information database. The researchers used the data to develop statistical models for gauging the effectiveness of HVCs at three uncontrolled intersections in Erie County, NY, one of six NDS test sites. They defined benchmark points before each intersection based on predictions of when drivers could see and react to the HVCs. Then they examined changes in speed, acceleration, and throttle pedal actuation as drivers passed through the intersections, both before and after HVCs were installed. Sarwar took that research to the next level by developing similar statistical models to analyze data from all six NDS test sites. The other five sites are in Florida, Indiana, North Carolina, Pennsylvania, and Washington. For more efficient and unbiased estimates of speed, acceleration, and throttle pedal actuation, Sarwar will develop statistical models that take into account correlations for each factor at the benchmark and crosswalk points. He plans to develop models for gauging the distance from a driver’s first application of the brakes to an HVC and the time it takes for the vehicle to slow to a minimum speed value.

IMPACT: By incorporating data from all six SHRP 2 test sites, Sarwar will create advanced statistical models for gauging how different HVC marking types and placements could improve pedestrian safety. The broader sampling of data also makes it possible to evaluate HVCs based on regional differences in driving behavior. Finally, Sarwar’s models can be used to pinpoint how far from HVCs to place warning signs as a prompt for drivers to slow their speed.

RESOURCES: Several publications and papers resulted from this RAP research. They are outlined below.

Sarwar, M. T., Fountas, G., & Anastasopoulos, P. C. (2017). Simultaneous estimation of discrete outcome and continuous dependent variable equations: A bivariate random effects modeling approach with unrestricted instruments. *Analytic Methods in Accident Research*, 16, 23–34.

Sarwar, M. T., Anastasopoulos, P. C., Golshani, N., & Hulme, K. (2017). Grouped random parameters bivariate probit analysis of perceived and observed aggressive driving behavior: A driving simulation study. *Analytic Methods in Accident Research*, 13, 52–64.

Anastasopoulos, P. C., Fountas, G., Sarwar, M. T., Karlaftis, M., & Sadek, A. (2017). Transport habits of travelers using new energy type modes: A random parameters hazard-based approach of travel distance. *Transportation Research Part C: Emerging Technologies*, 77, 516–528.

Nahidi, S., Fountas, G., Sarvani, S., Sarwar, M. T., & Anastasopoulos, P. C. (2017). Project discrepancies in roadway construction and preservation: A statistical analysis of public–private partnership contract types in the US. *Frontiers in Built Environment*, 3, 15, DOI: 10.3389/fbuil.2017.00015.

Sarwar, M. T., Fountas, G., Bentley, C., Anastasopoulos, P. C., Blatt, A., Pierowicz, J., Majka, K., & Limoges, R. (2017). Preliminary investigation of the effectiveness of high-visibility crosswalks on pedestrian safety using crash surrogates. *Transportation Research Record: Journal of the Transportation Research Board*, 2659, DOI:10.3141/2659-20.

Sarwar, M. T., Fountas, G., & Anastasopoulos, P. C. (2017). Analysis of stationary and dynamic factors affecting highway accident occurrence: A dynamic correlated grouped random parameters binary logit approach. *Accident Analysis and Prevention*, 113, 330–340.

Sarwar, M. T., Fountas, G., Bentley, C., Anastasopoulos, P. C., Blatt, A., Pierowicz, J., Majka, K., & Limoges, R. (2017). *Preliminary investigation of the effectiveness of high-visibility crosswalks on pedestrian safety using crash surrogates*. Presented at the 96th Transportation Research Board Annual Meeting, Washington, DC.

Fountas, G., Sarwar, M. T., & Anastasopoulos, P. C. (2017). *Analysis of stationary and dynamic factors affecting highway accident occurrence*. Presented at the 96th Transportation Research Board Annual Meeting, Washington, DC.

Golshani, N., Sarwar, M. T., & Anastasopoulos, P. C. (2017). *Exploratory empirical analysis of measured and perceived aggressive driving behavior in a driving simulation environment*. Presented at the 96th Transportation Research Board Annual Meeting, Washington, DC.



Human Behavior and Travel Choices

PROJECT: Data-Driven Space-Time Dependent Traffic Condition Estimation and Management

ASSOCIATE: Lin Xiao

SCHOOL: Hong Kong University of Science & Technology

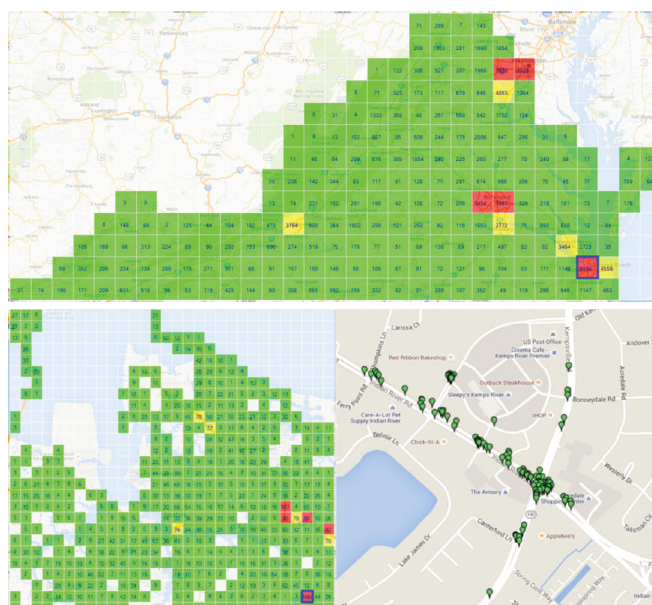
PERIOD: October 2015–June 2018

OBJECTIVE: To analyze the Strategic Highway Research Program 2 (SHRP 2) and other datasets to gain critical insights into the spatial, temporal, and causation patterns of traffic crashes; perform targeted analyses to uncover the underlying relationships between crashes and level of services in different types of land-use environments; and develop data-mining tools for identifying high-crash locations and extracting relevant crash record data for detailed further analysis.

ADVISER: Wei Zhang, FHWA Office of Safety Research and Development

SUMMARY: Lin Xiao conducted multi-dimensional analyses of datasets from SHRP 2, including the Roadway Information Database (RID), the Safety Pilot Dataset from Ann Arbor, MI, and statewide crash data from Virginia and Texas. The data he analyzed from the RID were primarily the geocoded statewide crash data from Florida, Indiana, New York, North Carolina, Pennsylvania, and Washington. Xiao developed tools for viewing, analyzing, and visualizing the large datasets. The most important tool he developed is 2-STEP, which reads in statewide crash data. In Step 1, an entire State is partitioned into grids of 10 mi². The grids are ranked by crash frequency and crash cost. In Step 2, the selected grids are further partitioned into grids of 0.5 mi², and the ranking process is repeated. The highlighted smaller grids are the ones with the highest number or highest cost of crashes. Based on the codes written for this tool, Xiao developed over a half-dozen other tools. These tools can analyze different types of geolocated data (crash, traffic flow, speed, etc.) and make various predictions. These additional tools can be used to:

- Identify traffic bottleneck locations and the peak periods.
- Identify the dates on which weather and other large-scale events caused significant changes to the daily crash frequency.
- Predict the annual crash frequency of any location based on historic, multi-year crash data.
- Merge naturalistic driving data from the Safety Pilot data collected in the Ann Arbor, MI, area with crash data to investigate the delays caused by different severities of crashes.
- Merge crash data with data from permanent traffic-counting stations, and assess the impacts of crashes to speed distribution (further refinement of this tool can lead to effective crash-detection algorithms).
- Predict time series trends.



An illustration of the 2-STEP tool at work, counterclockwise from top: Divide the entire region, the State of Virginia in this case, into a grid of 10 mi² and pick one for further analysis (Step 1); subdivide the highlighted grid in Step 1 into a grid of 0.5 mi² (Step 2); and identify a high-crash location. Source: FHWA.

Xiao contributed to the investigation of the relationship between crash severity and the level of traffic service using a neural network/machine-learning approach. He collaborated with other associates on research into connected vehicles and artificial intelligence.



Human Behavior and Travel Choices

IMPACT: Xiao's research makes it easier for practitioners to identify and extract useful information from SHRP 2 and other large datasets. These tools can provide the precise "where," "when," and "why" of traffic crashes in the identified high-crash areas, which provide actionable information for decisionmakers. Safety projects initiated based on the above information can increase the return on investment significantly and improve systemwide safety. His work produced the following mathematical and technological tools to help achieve those goals:

- A tool called 2-STEP for identifying high-crash locations based on multiyear, statewide (or other types of regional) crash data.
- A big data approach to predicting traffic crashes for any location in a State.
- An interactive tool for identifying traffic bottlenecks.
- An interactive tool for identifying the dates of large-scale events that significantly altered daily crash patterns.
- A methodology for assessing the relationship between crash severity and levels of traffic flow.
- Algorithms for identifying crash events based on permanent traffic counter data.

REASOURCES: Several publications and papers resulted from this RAP research. They are outlined below.

- Pan, D., C. Silverstein, L. Xiao, A. Caamaño, W. Zhang, and S. Hamdar. 2018. "Investigating the Relationship Between Collision Characteristics and Traffic Level of Service Through Big Data Analytics: A Case Study in the State of Virginia." Presented at the American Society of Civil Engineers' Transportation and Development International Conference. Pittsburgh, PA: American Society of Civil Engineers.
- Zhang, W., and L. Xiao. 2018. "Vulnerable Road User Crash Patterns in Orlando." Presented at the 18th Chinese Overseas Transportation Association's International Conference of Transportation Professionals. Beijing, China: Chinese Overseas Transportation Association.
- Zhang, W., L. Xiao, Y. Wang, and K. Kelarestaghi. 2018. "Big Data Approach of Crash Prediction." Presented at the 97th Annual Meeting of the Transportation Research Board. Washington, DC: Transportation Research Board.
- Wang, P., W. Wu, L. Wang, L. Xiao, X. Deng, and M. Li. 2017. "A Novel Cooperative Collision Avoidance Model for Connected Vehicles." *Transportation Research Record: Journal of the Transportation Research Board* 2645. <https://doi.org/10.3141/2645-16>.
- Kelarestaghi, K., W. Zhang, Y. Wang, L. Xiao, K. Hancock, and K. Heaslip. 2017. "Impacts to crash severity outcome due to adverse weather and other causation factors." *Advances in Transportation Studies* 43: 31–42.
- Wang, P., H. Yu, L. Xiao, and L. Wang. 2017. "Online traffic condition evaluation method for connected vehicles based on multisource data fusion." *Journal of Sensors*.
- Qu, X., S. Wang, T. Wang, L. Xiao, W. Yi, and Z. Liu. 2017. "Mixed-integer linear programming models for teaching assistant assignment and extensions." *Scientific Programming*.
- Ren, Y., Y. Wang, G. Yu, H. Liu, and L. Xiao. 2016. "An adaptive signal control scheme to prevent intersection traffic blockage." *IEEE Transactions on Intelligent Transportation Systems* 18, no. 6: 1519–1528.
- Zhao, Y., P. Huang, L. Xiao, J. Ma, J. Hu, and Y. Wang. 2017. "A scalable short-term origin-destination estimation approach based on modularized network with connected vehicle technology." Presented at the 96th Annual Meeting of the Transportation Research Board. Washington, DC: Transportation Research Board.
- Xiao, L., Y. Wang, J. Hu, and Y. Zhao. 2017. "Responsive signal control with active connected vehicles." Presented at the 96th Annual Meeting of the Transportation Research Board. Washington, DC: Transportation Research Board.



Human Behavior and Travel Choices

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

ASSOCIATE: Yubian Wang

SCHOOL: University of Texas at El Paso

PERIOD: October 2014–September 2017

OBJECTIVE: To conduct analytical and simulation studies to find suitable and implementable methods of analyzing innovative alternative intersection and interchange designs.

ADVISER: Wei Zhang, FHWA Office of Safety Research and Development

SUMMARY: Researchers and practitioners in the United States are exploring ways to improve highway safety and address traffic capacity issues in part by implementing innovative designs at intersections and interchanges. Yubian Wang spent 3 yr at TFHRC researching alternative intersection designs, including diverging diamond interchanges (DDIs), continuous-flow intersections (CFIs), and restricted crossing U-turn intersections (RCUTs). Alternative intersections/interchanges are designs aimed at reducing congestion and improving safety by reducing traffic conflicts rather than adding lanes. These designs take advantage of site-specific traffic demand patterns by introducing auxiliary intersections at strategic locations and rerouting certain traffic movements. The traffic conflicts at the primary intersection can be reduced by 50 percent or more, and some previously conflicting movements become compatible and can move simultaneously. Alternative designs typically eliminate the protected left-turn phase and increase effective green-light time for other traffic movements, which usually translate into more capacity with minimal or no increases in the intersections' right of way. In fully developed areas, alternative designs are often the only effective and fiscally viable solution to congestion and safety problems that plague the Nation's roadway network.

Wang's work filled some critical gaps in this area and has been applied to solve real work problems. She reviewed relevant literature to synthesize best practices for DDI, CFI, and RCUT designs. The review covered operational and safety performance of the designs, their challenges and limitations, and lessons learned from building and operating them. She also traveled to alternative intersection sites in Haymarket, Norfolk, and Vienna in Virginia to see firsthand how different types of field data are collected and used to assess different performance aspects of alternative designs. Wang expanded the research work of a previous postdoctoral fellow and helped deliver critical technical

assistance to many State and local agencies. In 2015, the Georgia Department of Transportation (GDOT) decided to design a future DDI at I-285 and Camp Creek Parkway in Atlanta. Wang took a leading role in performing the simulation analysis to evaluate the impacts of different alternative designs and signal-timing strategies. During a period of over 4 mo, the research team (including Wang) presented the simulation results in multiple online conferences, the GDOT staff provided feedback, and the simulation models were refined to make the simulated conditions closer to field conditions.

Wang thoroughly analyzed the before- and after-crash data of more than 150 modern roundabouts in 6 States, and she developed crash-modification factors for single-lane and multilane roundabouts converted from previous stop- or signal-controlled intersections. This is one of the largest number of roundabouts included in a single study. Wang manually examined the satellite images of each site by year to verify if the previous type of traffic control device was coded correctly, sorted through the crash records and organized them into unified formats, and analyzed the data using various statistical models.

Wang also contributed to big data research in which she helped develop models to predict the frequency and economic cost of traffic crashes in a region.



Human Behavior and Travel Choices

IMPACT: DDIs, CFIs, and RCUTs can reduce the number of traffic signal phases and conflict points, but these designs are still relatively new to most traffic engineers. Wang's work helped convince practitioners to implement alternative intersection designs at more suitable locations. Her work with GDOT provides insight into how different geometric designs and signal-timing strategies could improve the level of service. A congested signal intersection sitting next to a high-capacity DDI would limit the capacity utilization of the DDI. Wang helped advance the state of the art in solving this class of problem. Her analysis of roundabouts filled a critical gap in safety impacts of converting existing stop- or signal-controlled intersections into yield-controlled modern roundabouts.

RESOURCES: Several publications and papers resulted from this RAP research. They are outlined below.

- Zhang, W., L. Xiao, Y. Wang, and K. Kelarestaghi. 2018. "Big Data Approach of Crash Prediction." Presented at the 97th Annual Meeting of the Transportation Research Board. Washington, DC: Transportation Research Board.
- Kelarestaghi, K., W. Zhang, Y. Wang, L. Xiao, K. Hancock, and K. Heaslip. 2017. "Impacts to Crash Severity Outcome Due to Adverse Weather and Other Causation Factors." *Advances in Transportation Studies* 43: 31–42.
- Wang, Y., Y. Zhao, W. Zhang, J. Bared, and P. Huang. 2017. "Signal Timing Strategies for Georgia's First In-House Designed DDI." Presented at the 5th Urban Street Symposium. Raleigh, NC: Transportation Research Board and Institute of Transportation Engineers North Carolina Section.
- Wang, Y., and R. L. Cheu. 2016. "Operational impacts of implementing auxiliary lanes at isolated freeway off-ramps." *ITE Journal* 86: 36–41.
- Wang, Y., and W. Zhang. 2016. "Analysis of Roadway and Environmental Factors Affecting Traffic Crash Severities." *Transportation Research Procedia* 25: 2124–2130.
- Hancock, K., W. Zhang, H. Sardar, and Y. Wang. 2016. "A Two-Step Geo-Grid Screening Process to Identify Locations for Safety Improvements." *Advances in Transportation Studies: An International Journal* 2: 89–102.
- Zhang, W., K. Hancock, Y. Wang, and H. Sardar. 2015. "Estimate Economic Losses Due to Roadway Crashes." Presented at the 2015 Road Safety and Simulation International Conference. Orlando, FL: University of Central Florida and University of Tennessee, Knoxville.
- Zhang, W., K. Hancock, Y. Wang, and H. Sardar. 2016. "Prioritize Safety Projects with Confidence Using Two-Step Spatial Screening." Presented at the ASCE International Conference on Transportation and Development. Houston, TX: American Society for Civil Engineers.



Human Behavior and Travel Choices

PROJECT: Integrating Driving Simulation and Other Behavioral Data: Assessment of Driver Behavior and Performance

ASSOCIATE: Alicia Romo

SCHOOL: The University of Texas at El Paso

PERIOD: September 2013–July 2015

OBJECTIVE: To develop methods that will use data from various sources, such as driving simulator experiments, crash databases, and naturalistic driving studies, to gain comprehensive understanding about road-user behaviors.

ADVISER: C. Y. David Yang, FHWA Office of Safety Research and Development

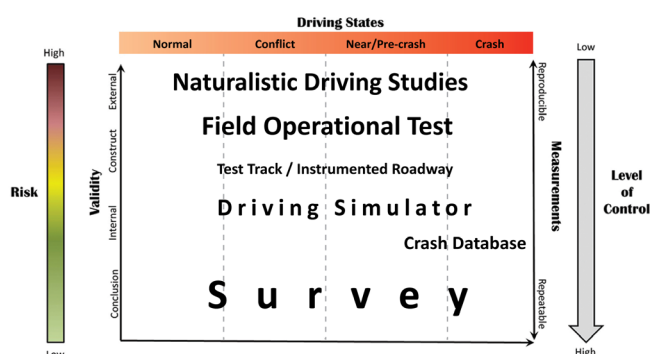
SUMMARY: A high percentage of transportation incidents and vehicle crashes are caused by human errors. As a result, it is important to continue investing in research resources to gain a comprehensive understanding of human errors and to try to answer the question, “Why do drivers and travelers do what they do?” A number of different datasets have recently become available to analyze human errors; however, these datasets point in different directions within different areas of interaction. Alicia Romo’s research project is focused on finding methods to combine data from different sources to gain better understanding about road-user behavior. During the first year, Romo conducted a comprehensive literature review and summarized information from more than 100 technical journals and reports about various methods to study road-user behavior and types of available behavioral data. Based on the information from this literature review, Romo has since developed a framework to categorize behavior data from various sources, such as crash databases, driving simulator experiments, field test vehicle studies, and naturalistic driving studies. Romo’s research will show the benefit of using information from multiple data sources to study behavioral issues instead of relying on just one data source.

IMPACT: This research project demonstrated one or more methods of using data from various sources to better understand road-user behavior. The concept of combining and using behavioral data from multiple sources is relatively new, and this work will pave the way for others to follow. Results from this project showed many benefits of combining data to better understand behavior issues. Integration of human behavior collected using different methods could lead to faster design and testing of safety countermeasures and new geometric designs, resulting in fewer crashes and potentially saved lives. The integration of different human behavior data also could provide safe and effective methods for studying and testing emerging connected-vehicle and automation technologies..

RESOURCES: Several publications resulted from this RAP research. They are outlined below.

Romo, A., Mejia, B., & Yang, C. Y. D. (2014). *Utilizing various data sources for surface transportation human factors research: workshop summary report* (Publication No. FHWA-HRT-14-077). FHWA Turner-Fairbank Highway Research Center, McLean, VA. Available online: <http://www.fhwa.dot.gov/advancedresearch/pubs/14077/index.cfm>.

Romo, A., Yang, C. Y. D. (2015). The science and art of putting drivers under the microscope. *Public Roads*, 78(5). Federal Highway Administration Pub. No. FHWA-HRT-15-003. Available online: <https://www.fhwa.dot.gov/publications/publicroads/15marapr/04.cfm>.



The relationship between research methods and impacting factors. Source: FHWA

Note: There are five empirical factors that can be used to evaluate the quality of data and the analysis performed. The five factors are: driving states, risk, level of control, measurements, and validity. The five factors presented in this figure explain the similarities, differences, advantages, and disadvantages among the different research methods.



Human Behavior and Travel Choices

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

ASSOCIATE: Nopadon Kronprasert

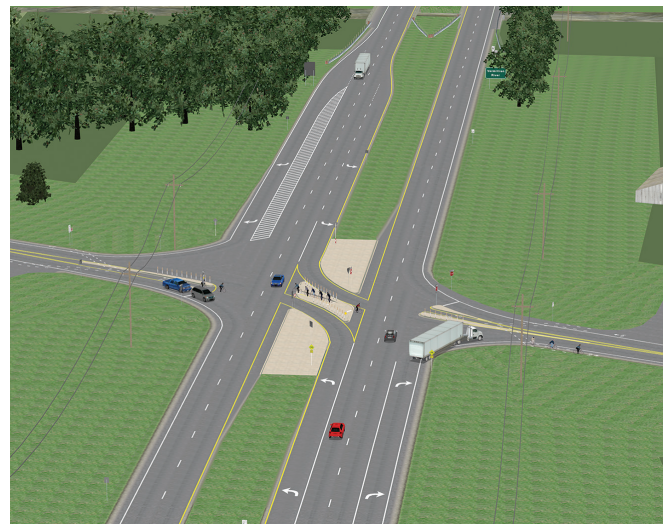
SCHOOL: Virginia Polytechnic Institute and State University

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 Research and Development

SUMMARY: Transportation and traffic professionals working on today's highway improvement projects face daunting pressures from the needs of different stakeholders to provide safe, efficient, and cost-effective intersections and interchanges. FHWA recently proposed several alternative intersection and interchange designs to improve the safety- and mobility-related issues across the Nation. These new intersections and interchanges include displaced left-turn, median U-turn, and restricted-crossing U-turn intersections, as well as the double-crossover diamond interchange. It is important to evaluate how efficient the new designs will be and to identify the traffic conditions that will deliver the best cost-benefit performance. In accordance with this objective, Nopadon Kronprasert's research project investigated operational and safety measures and evaluation procedures, analyzed proposed designs at different evaluation sites, and developed mathematical models for evaluating operational and safety measures for different intersection and interchange designs. Kronprasert used a microscopic trafficsystems simulation of model characteristics and behaviors to evaluate the performance of alternative designs. This simulation is a cost-effective method to compare different designs, predict potential impacts, replicate real-world phenomena, and provide valuable insights into the effects on operational and safety performance. Kronprasert conducted his research based on problems derived from real projects. As part of the technical support to State departments of transportation, he performed traffic simulation studies of three double-crossover diamond interchanges, three restricted-crossing U-turn intersections, and six mini-roundabout projects.



A screen capture of an intersection based on Nopadon Kronprasert's simulation input. © Wei Zhang, Nopadon Kronprasert, and Jason Williams.



An aerial view of a two-cloverleaf highway interchange from a simulation video created by Nopadon Kronprasert. © Wei Zhang, Nopadon Kronprasert, and Jason Williams.

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 also will help highway engineers and the public understand the benefits and impacts.

RESOURCES: Several publications and papers resulted from this RAP research. They are outlined below.

- Krause, C., N. Kronprasert, J. Bared, and W. Zhang. 2015. "Operational Advantages of Dynamic Reversible Left-Lane Control of Existing Signalized Diamond Interchanges." *Journal of Transportation Engineering* 141, no. 5.
- Zhang, W., and N. Kronprasert. 2014. "The ABCs of Designing RCUTs." *Public Roads* 78, no. 2: 9–13.
- Zhang, W., and N. Kronprasert. 2014. "Unlock DDI's Capacity Potential by Implementing Relaxed Bowtie, Superstreet, And Quadrant Road Design at Adjacent Signal Intersections." Presented at the Second International Conference on Access Management. Shanghai, China: Transportation Research Board.
- Zhang, W., and N. Kronprasert. 2014. "Unlock Diverging Diamond Interchange's Capacity Potential Using Relaxed Bowtie Design at Adjacent Signalized Intersection." Presented at the Transportation Research Board's Alternative Intersections and Interchanges Symposium. Salt Lake City, UT: Transportation Research Board.
- Zhang, W., and N. Kronprasert. 2014. "Crash Prediction Models for Rural Restricted Crossing U-Turn Intersections." Presented at the Transportation Research Board's Alternative Intersections and Interchanges Symposium. Salt Lake City, UT: Transportation Research Board.
- Zhang, W., and N. Kronprasert. 2014. "Mini-Roundabout Case Studies." Presented at the Transportation Research Board's International Roundabout Conference. Seattle, WA: Transportation Research Board.
- Zhang, W., N. Kronprasert, and J. Gustaffson. 2014. "Unclog Local Network Congestion Using High-Capacity Mini-Roundabouts: A Feasibility Study." Presented at the 93rd Annual Meeting of the Transportation Research Board. Washington, DC: Transportation Research Board.
- Lochrane, T., N. Kronprasert, J. Bared, D. Dailey, and W. Zhang. 2014. "Determination of Mini-Roundabout Capacity in the United States." *Journal of Transportation Engineering* 140, no. 10.
- Zhang, W., and N. Kronprasert. 2016. "System intersections—Concepts, Simulation Studies, And Potential Applications." Presented at the International Conference on Transportation and Development 2016. Houston, TX: American Society of Civil Engineers.
- Zhang, W., and N. Kronprasert. 2014. "Unlock DDI's Capacity by Re-Routing Left-Turns at Nearby Intersections." Presented at the Conference on Access Management Theories and Practices. Shanghai, China: Transportation Research Board. <https://ascelibrary.org/doi/10.1061/9780784413869.020>.

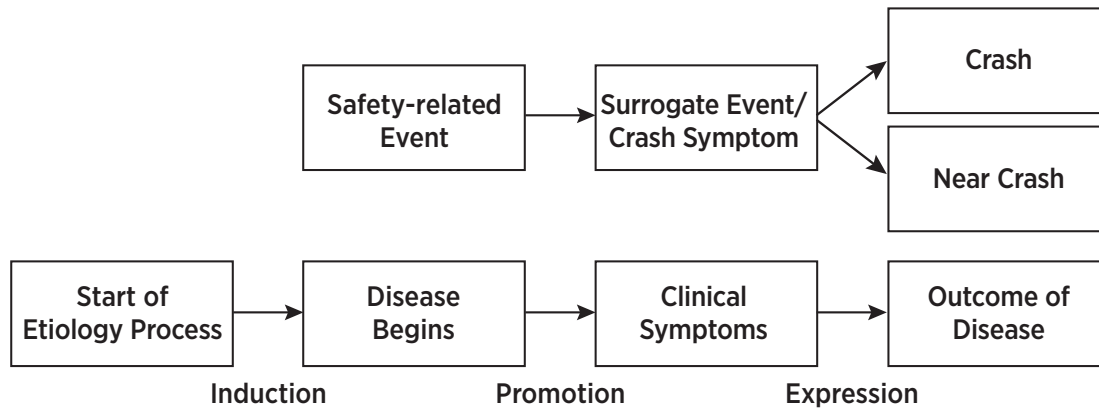


Human Behavior and Travel Choices

- PROJECT:** Utilizing Naturalistic Driving Data and Highway Safety Information System to Advance Highway Crash Data Modeling Concepts and Methods
- ASSOCIATE:** Kun-Feng Wu
- SCHOOL:** Pennsylvania State University
- PERIOD:** July 2012–June 2013
- OBJECTIVE:** To advance safety analysis using surrogate safety measures and improve the evaluation of intervention effectiveness.
- ADVISER:** Craig P. Thor, FHWA Office of Safety Research and Development

SUMMARY: Kun-Feng Wu's research project builds on 40 years of research concerning the development of crash surrogates for assessing traffic safety. The term *crash surrogate* refers to a crash or near-crash event, defined in this project by a set of driver or event attributes, driving environment, and kinematic variables. Researchers use crash surrogates because crashes are rare events, making it hard to draw statistically valid conclusions about contributing factors. Surrogate event counts can be used to predict the expected number of crashes and identify sites with promise for improvement by knowing the number of surrogate events at each intersection. Wu investigated a sequence of statistical tests with the overall goal of validating surrogate events and facilitating their use in enhanced safety analyses. Wu used raw naturalistic driving data, including vehicle kinematic, video, and location information, to produce sets of specific conditions that identify crashes and near crashes (i.e., surrogate events). Wu tested the procedure on a small, 100-car naturalistic driving study dataset, conducted by the

Virginia Tech Transportation Institute, with successful results. A second validation procedure compared these results with the number of crashes observed in HSIS data, a multistate database that contains crash, roadway inventory, and traffic volume data for a select group of States. Wu's research extends research already completed in the joint use of crash events and surrogate events in a structured framework. His research project specifically compared surrogate analyses of countermeasure effectiveness and sites with improvement potential to comparable HSIS studies. Wu applied the same methods to evaluate the Integrated Vehicle-Based Safety System dataset (an initiative designed to develop and field test an integrated safety system on light vehicles and commercial trucks). In addition, Wu expanded the procedures to include diagnostic analytical techniques borrowed from medical science. These statistical methods allow for a more accurate assessment of the presence of surrogate events.



A schematic that relates the crash progression process to the etiological process of disease progression. © Kun-Feng Wu

IMPACT: Specific conditions for defining surrogate events could be further tested and studied through driving performance assessment and may ultimately lead to improved understanding of inappropriate driving behaviors, driver responses, roadway design, and operational deficiencies. In addition, crash surrogate studies could ultimately reduce the time needed to develop a sufficient sample size for analysis. These studies would enable researchers to develop models with greater prediction precision and understand the factors that contribute to crashes. Decreasing the time and increasing the precision of factors that contribute to crashes allow faster development and implementation of better countermeasures, thereby reducing crashes and potentially saving lives.

RESOURCES: The papers that resulted from this RAP research are outlined below.

- Wu, K. F., Thor, C., & Ardiansyah, M. N. (2016). Identify sequence of events likely to result in severe crash outcomes. *Accident; Analysis and Prevention*, 96:198–207.
- Wu, K. F., & Thor, C. (2015). Method for the use of naturalistic driving study data to analyze rear-end crash sequences. *Transportation Research Record, Journal of the Transportation Research Board*, 2518(2518):27–36.



Technology for Assessing Performance

PROJECT: Artificial Intelligence-Aided Bridge Condition Assessment System Using Deep Learning Approaches

ASSOCIATE: Heng Liu

SCHOOL: University of Maryland

PERIOD: January 2019–November 2021

ADVISER: Jean Nehme, FHWA Office of Infrastructure Research and Development

SUMMARY: During his RAP tenure, Heng Liu developed two condition forecast models for the FHWA Long-Term Bridge Performance InfoBridge™ web portal. He also published one peer-reviewed journal paper and made several presentations at the Transportation Research Board annual meeting and various FHWA meetings and webinars.

RESOURCES: His research work resulted in one published peer-reviewed journal paper:

Liu, H., J. Nehme, P. Lu. 2021. "An Application of Convolutional Neural Network for Deterioration Modeling of Highway Bridge Components in the United States." *Structure and Infrastructure Engineering*. <https://doi.org/10.1080/15732479.2021.1979597>, last accessed November 17, 2021.

PROJECT: Integration of Machine Learning into Long Term Pavement Performance Prediction Models

ASSOCIATE: Adel Rezaei-Tarahomi

SCHOOL: Iowa State University

PERIOD: June 2019–July 2021

ADVISER: Jean Nehme, FHWA Office of Infrastructure Research and Development

SUMMARY: During his RAP tenure, Adel Rezaei-Tarahomi did the following:

- Leveraged machine learning, artificial neural networks, and data analytics to employ unstructured and structured data toward pavement performance predictions for saving materials and time spent during experimental lab tests.
- Created optimized XGBoost model pipeline in Python by using TensorFlow, Keras, and Scikit-learn's GridSearch that achieved 98 percent accuracy, which is a 20–30 percent improvement in binder performance prediction accuracy compared to the conventional regression models.
- Devised and automated a method for converting 360 degree-images of the circumference of cylindrical asphalt specimen to a 2D flat image by using image-stitching technique, OpenCV, Pandas, and NumPy in Python.
- Conceptualized and developed a machine learning-based web application by Python, Dash, Flask, HTML, and CSS and deployed it to the Heroku cloud platform.
- Developed an analytical PowerBI dashboard to visualize the impacts of COVID-19 restrictions on travel speed and collision in the state of Maryland.



Technology for Assessing Performance

PROJECT:	Developing Probabilistic Bridge Deterioration Models Based on Nondestructive Evaluation of Concrete Bridge Decks Using Multiple NDE Technologie
ASSOCIATE:	Raka Goyal
SCHOOL:	University of North Carolina at Charlotte
PERIOD:	September 2018–July 2021
OBJECTIVE:	To develop a framework for multivariable probabilistic bridge deterioration model.
ADVISER:	Jean Nehme , FHWA Office of Infrastructure Research and Development

SUMMARY: Raka Goyal developed a framework for multivariable probabilistic bridge deterioration model development using the entire national bridge inventory (NBI) data from 1983 to 2019 for more than 6000,000 bridges nationwide. The proportional hazards (PH) bridge deterioration models are based on a combination of survival analysis and Markov-chain theory. She developed 50-yr forecasts of bridge component condition ratings for all bridges and culverts in the NBI using the developed nationwide PH bridge deterioration models. Her work enabled implementation of the condition rating forecast dashboard on FHWA InfoBridge web portal. Goyal also developed the PH bridge network performance forecast models for bridges nationwide, enabling InfoBridge users to develop 50-yr network performance forecasts for selected groups of bridges from the entire NBI. Her work enabled the development of the performance forecast dashboard of FHWA InfoBridge.

RESOURCES: Several publications and papers resulted from this RAP research. They are outlined below.

- Goyal, R., Whelan, M., and T. Cavalline. 2020. "A Multivariate Proportional Hazards-Based Probabilistic Model for Bridge Deterioration Forecasting." *Journal of Infrastructure Systems* 26, no. 2: 04020007.
- Goyal, R., Whelan, M. and T. Cavalline. 2019. "Duration-based Forecasting of Bridge Condition with Non-Parametric Kaplan-Meier Survival Functions." Presented at the 5th International Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures. Potsdam, Germany: German Society for Non-Destructive Testing.
- Goyal, R. and J. A. Nehme. n.d. "Bridge Network Performance—Survival-Based Models" (web page). https://infobridge.fhwa.dot.gov/Content/Documents/Models/Bridge_Network_Performance_Forecast_Survival_Based_Models.pdf, last accessed November 8, 2021.
- Goyal, R. n.d. "Bridge Condition Rating Forecast-Survival-Based Models" (web page). https://infobridge.fhwa.dot.gov/Content/Documents/Models/Bridge_Component_Condition_Forecast_Survival_Based_Models.pdf, last accessed November 8, 2021.
- Goyal, R. 2021, "Bridge Condition Forecasting-Survival-Based Models" 100th Annual Meeting of the Transportation Research Board. Washington, DC: Transportation Research Board.
- Goyal, R. 2020. "Nationwide Survival-Based Bridge Deterioration Models." Presented at the 99th Annual Meeting of the Transportation Research Board. Washington, DC: Transportation Research Board.
- Goyal, R. 2019. "Proportional Hazards-based Probabilistic Models for Bridge Deterioration Forecasting." Presented at the 98th Annual Meeting of the Transportation Research Board. Washington, DC: Transportation Research Board.



Technology for Assessing Performance

PROJECT: Numerical and experimental study of air-coupled impact-echo and ultrasonic surface waves for in situ condition monitoring of concrete structures

ASSOCIATE: Mohammadmehdi Nikirashidi

SCHOOL: Georgia Institute of Technology

PERIOD: August 2018–April 2020

OBJECTIVE: To assess the overall condition of bridge decks using the Jensen-Shannon divergence of nondestructive evaluation (NDE) data.

ADVISER: Hoda Azari, FHWA office of Infrastructure Research and Development

SUMMARY: Nikirashidi's research work involved:

- Assessing the overall condition of bridge decks using the Jensen-Shannon divergence of nondestructive evaluation (NDE) data. This research aimed to quantify the differences between NDE results represented in the form of probability distributions, and use such information to develop a bridge deck rating index. To this end, the results from multiple NDE technologies on the Haymarket, VA bridge deck were represented in the form of probability distributions. The deviation of these probability distributions from ideal distributions representing an intact condition of the bridge deck, was quantified using the square root of the Jensen-Shannon divergence ($\sqrt{\text{JSD}}$). An NDE rating index, in the range of 0–10, was suggested using $\sqrt{\text{JSD}}$, and it was used to develop the deterioration curve of the deck. Results demonstrated the effectiveness of this approach for the assessment of the overall condition and deterioration modeling of bridge decks.
- Conducting quality control of nondestructive evaluation data collected with a robotic-assisted bridge inspection tool (RABIT). This research aimed to draw attention to the importance of the data reliability issue during the automated nondestructive evaluation of bridge decks. RABIT-collected data suffering from the malfunction of the system were presented, and a procedure for the improvements of the impact-echo results was suggested. For electrical resistivity data, a protocol to investigate the local outliers was proposed. It was suggested to include a companion contour map representing the reliability of data with each NDE technology.
- Using noise reduction of a multichannel acoustic scanning tool (MAST) and developing a signal processing procedure for the analysis of acoustic data to overcome the practical challenges associated with the traditional acoustic techniques. Special care was taken to minimize the acoustic noise and the vibration of components within the device. A signal processing procedure was suggested to amplify and capture the signal of interest. The performance of MAST on a lab-produced reinforced concrete slab and slabs obtained from a bridge deck was assessed. The system inspected the slabs at a high speed, and it was capable of detecting shallow and deep delamination in concrete slabs. Results suggested great potential for the field application of the system.
- Performing fully noncontact acoustic measurements. In this research, a noncontact transducer excited the surface of concrete using pulses of a broadband chirp signal (5–55 kHz), and a micromechanical systems microphone received the signal. In the presence of shallow delamination, a clear delay in the group velocity of signals with frequencies between 20–30 kHz was observed. Results, interpreted in the context of lab wave, suggest mode conversion of surface waves in the presence of delamination.

RESOURCES: Several publications and papers resulted from this RAP research. They are outlined below.

Rashidi, M., H. Azari, and J. Nehme. 2019. "Assessment of the Overall Condition of Bridge Decks Using the Jensen-Shannon Divergence of NDE Data." *NDT and E International* 110, no. 2020: 102204.

Hoda, A., and R. Mehdi. 2019. "Speeding Up Bridge Deck Evaluations." *Public Roads* 83, no.3.



Technology for Assessing Performance

PROJECT:	Networks for Interpretation of Nondestructive Evaluation of Bridges
ASSOCIATE:	Sattar Dorafshan
SCHOOL:	Utah State University
PERIOD:	June 2011–May 2013
OBJECTIVE:	To investigate the feasibility of using deep learning models (DLMs) for autonomous subsurface defect detection in bridge decks using Impact Echo has been investigated.
ADVISER:	Hoda Azari

SUMMARY: Impact echo (IE) is a common NDE method to detect subsurface defects in concrete bridge decks. The conventional approach for analyzing the IE data requires user expertise to define analysis parameters that could hinder broad field implementation. In this paper, the feasibility of using deep learning models for autonomous subsurface defect detection in bridge decks using IE has been investigated. A set of exiting IE data from eight laboratory-made reinforced concrete bridge specimens with artificial defects, constructed at the FHWA Advanced Sensing Technology NDE laboratory, were annotated based on the presence and type of subsurface defects. Two annotated IE datasets were generated: A total number of 2016 of IE data from bare specimens, and a total of 1,827 IE data from specimens with overlay. Several convolutional neural networks based on deep learning, were developed, trained, tuned, and tested on the annotated datasets. The most successful model was able to produce accuracy of 0.88 by classifying 0.70 of the defects and 0.95 of the sound regions correctly in the bare specimens. The proposed 1DCNN was superior to previous machine learning models that were previously used for IE classification. The proposed 1D CNN was the most successful in detecting debonding and subsurface defects in the overlay dataset; it achieved an average accuracy of 0.68 on the cement overlay specimens and 0.58 for asphalt overlay specimens. Maps of the defects in decks and defects in overlay were generated using the DLMs and were compared to the conventional method for analyzing the IE data. The 1D CNN produced the most accurate defect maps while successfully detected sound, debonded, and defected region. The results of this study showed the feasibility and the potentials of the DLMs for subsurface defect detection using IE for the first time.

IMPACT: The models produced in this project were the first successful implementation of deep learning for NDE data interpretation. The results are promising and showed deep learning and AI can be used for full bridge deck evaluation by detection of subsurface defects in an autonomous manner.

RESOURCES: Several publications and papers resulted from this RAP research. They are outlined below.

- Dorafshan, S., and H. Azari. 2020. "Deep learning models for bridge deck evaluation using impact echo." *Construction and Building Materials* 263: 120109.
- Dorafshan, S., and H. Azari. 2020. "Evaluation of Bridge Decks with Overlays Using Impact Echo, a Deep Learning Approach." *Automation in Construction* 113: 103133.
- Dorafshan, S., and H. Azari. 2020. "Artificial Intelligence for IE and GPR Data Analysis." Presented at the 101th Annual Meeting of the Transportation Research Board. Washington, DC: Transportation Research Board.
- Dorafshan, S., and H. Azari. "Federal Highway Administration NDE Program Vision for 21st Century Bridge Data." Presented at the Bridging Big Data 2019 Workshop. Lincoln, NE: University of Nebraska-Lincoln.
- Dorafshan, S., and H. Azari, H. 2019. "Advanced NDE Data Analysis Procedure Including the Use of Deep Learning" Presented at the 19th US-Korean Roads Workshop. Washington, DC: Federal Highway Administration and Republic of Korea Ministry of Land, Infrastructure and Transport.



Technology for Assessing Performance

PROJECT: Air-Coupled Acoustic and Ultrasonic Arrays for Concrete Nondestructive Test Methods

ASSOCIATE: Hajin Choi

SCHOOL: University of Illinois

PERIOD: January 2017–February 2018

OBJECTIVE: To develop air-coupled acoustic and ultrasonic arrays for non-destructive evaluation of concrete damage or property.

ADVISER: Hoda Azari, FHWA Office of Infrastructure Research and Development

SUMMARY: The large size of concrete structures, the time required to adequately inspect them, and the rough texture of the material pose challenges to the use of acoustic non-destructive test (NDT) methods for condition assessment of highway infrastructure. This research project by Hajin Choi aimed to develop an air-coupled acoustic and ultrasonic array as a contact-free NDT alternative to the conventional acoustic technology. Air-coupled sensors measure leaky Rayleigh waves without physical contact on the concrete being tested. The research encompassed four tasks. First, Choi developed an air-coupled acoustic array for two testing methods, impact-echo (IE) and ultrasonic waves (USW). Both methods generate stress waves and measure how they reflect off the concrete to identify flaws in the material. After developing the air-coupled system, Choi evaluated the system by collecting signal data from a test sample in FHWA's specimen library. He evaluated the speed of data collection, the signal-to-noise ratio, and the accuracy of test results. Next, Choi analyzed USW from the hybrid test setup and used the data to develop a linear formula for predicting various types of concrete damages. For the final task of the project, Choi applied the new air-coupled acoustic array and NDT parameters to a robotic platform for inspecting bridge decks to evaluate their practical use, and he described the tests, results, and analysis in a final report.

IMPACT: The research illustrates the potential of air-coupled acoustic arrays to increase the speed of conventional NDT for condition assessment of highway infrastructure. The possible field uses include IE and USW testing.

RESOURCES: Several publications and papers resulted from this RAP research. They are outlined below.

- Choi, H., & Azari, H. (2017). Guided wave analysis of air-coupled impact-echo in concrete slab. *Computers and Concrete*, 20(3), 257–262.
- Choi, H., Sadegh, S., & Azari, H. (2017). The improvement of impact-echo method using hybrid system and guided wave analysis. *Proceedings in International Conference on Maintenance and Rehabilitation of Constructed Infrastructure Facilities*.
- Choi, H., Sadegh, S., & Azari, H. (2017). NDE application of air-coupled array for thickness of concrete slab. *Proceedings in International Ultrasonics Symposium*.
- Choi, H., Sadegh, S., & Azari, H. (2017). *Application of air-coupled ultrasonic array system and f-k domain analysis for delamination-like defect detection in bridge deck*. Presented at the IEEE International Ultrasonic Symposium, Washington, DC.
- Choi, H., Sadegh, S., & Azari, H. (2017). *The improvement of impact-echo method using hybrid system and guided wave analysis*. Presented at the International Conference on Maintenance and Rehabilitation of Constructed Infrastructure Facilities, Seoul, Korea.



Technology for Assessing Performance

PROJECT: Prediction of Pavement Temperature Profiles Using Surface Temperatures: An Analytical Approach With Model Validation Based on Long-Term Pavement Performance Data

ASSOCIATE: Dong Wang

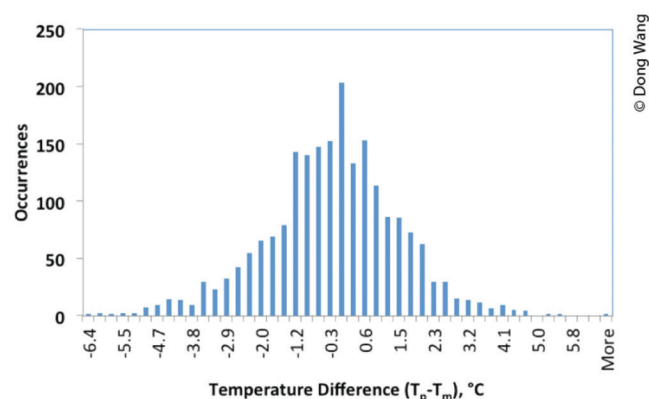
SCHOOL: University of Illinois at Urbana-Champaign

PERIOD: June 2011–May 2013

OBJECTIVE: To derive and field-validate an easily implementable algorithm for predicting temperature profiles in paving materials.

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SUMMARY: The mechanical properties of paving materials are usually temperature-dependent, but to accurately back-calculate the elastic moduli of pavement layers (i.e., the pavement’s resistance to being deformed elastically when a force is applied to it), time-dependent pavement temperature must be known. Knowing the temperature profile allows researchers to better characterize the properties of paving materials and predict pavement responses under traffic and environmental loadings. Dong Wang’s research project investigated a new method for predicting time-dependent pavement temperature profiles with limited inputs. There are currently three main methods for predicting temperature profiles: statistics-based models, numerical, and analytical approaches. These existing methods require large databases of climatic, meteorological, and geographical data and several other inputs to predict temperatures for the algorithms to operate effectively. Current pavement-testing methods do not easily obtain the required climatic data; thus, these algorithms are subsequently limited in their ability to predict pavement temperature profiles. Wang focused his research effort on infrared pavement surface temperature data that can be easily obtained during pavement testing. This improved approach makes it possible to develop an entirely new algorithm for predicting a time-dependent pavement temperature profile that requires very limited inputs when compared with previous algorithms. The only inputs needed for this new method are infrared surface temperatures, initial pavement temperature profile, pavement geometry, and thermal properties of layer materials. Most important, unlike previous methods, no climatic data are required. To validate the new algorithm, when there are so many different types of pavement structures across regions with varied climatic conditions, an extremely large temperature dataset is required. To meet this requirement, Wang used data from the Long-Term Pavement Performance (LTPP) Program database for model validation.



Histogram of asphalt pavement subsurface temperature difference (predicted (T_p)-measured (T_m) temperature difference). Source: FHWA.

IMPACT: Wang’s research is expected to greatly benefit field engineers in characterizing pavement temperature for the purpose of analyzing and interpreting testing data. In addition, it could lead to high savings on pavement evaluation costs.



Technology for Assessing Performance

RESOURCES: Several publications and papers resulted from this RAP research. They are outlined below.

Wang, D. (2013). Prediction of asphalt pavement temperature profile during FWD testing: A simplified analytical solution with model validation based on LTPP data. *Journal of Transportation Engineering*, 139(1), 109–113.

Wang, D. (2012). Analytical approach to predict temperature profile in a multilayered pavement system based on measured surface temperature data. *Journal of Transportation Engineering*, 138(5), 674–679.

Wang, D. (2013). Simplified analytical approach to predict asphalt pavement temperature. *Journal of Materials in Civil Engineering*, 27(12).

Wang, D. (2013). Prediction of asphalt pavement temperature profile during FWD testing: simplified analytical solution with model validation based on LTPP data. *Journal of Transportation Engineering*, 139(1).

Wang, D. (2012, July 5–7). *Prediction of time-dependent temperature profile in a slab*. Paper presented at the Third Advanced Workshop on Innovations and Modeling for Sustainable and Resilient Concrete Pavements, Quebec, Canada.

Wang, D. (2013, January 13–17). *Assessing BELLS3 equation in predicting asphalt layer temperature profile based on the latest LTPP FWD temperature data*. Paper presented at the 92nd Transportation Research Board Annual Meeting, Washington, DC.

Wang, D. (2013, January 13–17). *Simplified analytical approach to predict temperature profile within a PCC slab during FWD testing*. Paper presented at the 92nd Transportation Research Board Annual Meeting, Washington, DC.

Wang, D. (2012, January 22–26). *Model validation based on LTPP data to predict asphalt temperature profile*. Paper presented at the 91st Transportation Research Board Annual Meeting, Washington, DC.

Wang, D. (2012, January 22–26). *Prediction of temperature profile in a multilayered pavement system using measured surface temperature data: An analytical approach*. Paper presented at the 91st Transportation Research Board Annual Meeting, Washington, DC.

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EXPLORATORY ADVANCED RESEARCH



Recommended Citation: Federal Highway Administration,
Research Associates Program 2021 (Washington, DC: 2021)
<https://doi.org/10.21949/1521709>.

FHWA-HRT-22-024
HRTM-30/12-21(WEB)E



U.S. Department of Transportation
Federal Highway Administration