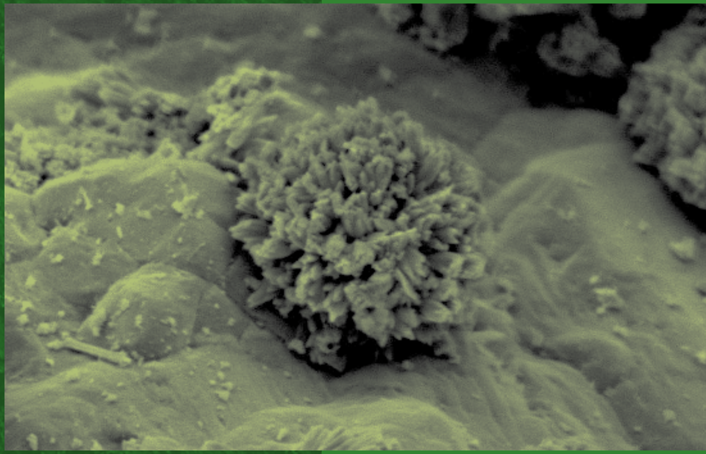
Exploratory Advanced Research Program

Research Associates Program 2018

EXPLORATORY ADVANCED RESEARCH



U.S. Department of Transportation
Federal Highway Administration

Notice

Quality Assurance Statement

Cover photos

Left: A simulation input illustrates EAR Program research associate Nopadon Kronprasert s work on alternative intersection and interchange designs (see page 23).

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 (see page 12).

Contents

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.

The EAR Program addresses the need for longer term, higher risk research with the potential for long-term improvements to transportation systems. The EAR Program seeks to leverage advances in science and engineering that could lead to breakthroughs for critical, current, and emerging issues in highway transportation by experts from different disciplines who have the talent and interest in researching solutions and might not do so without EAR Program funding.

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–

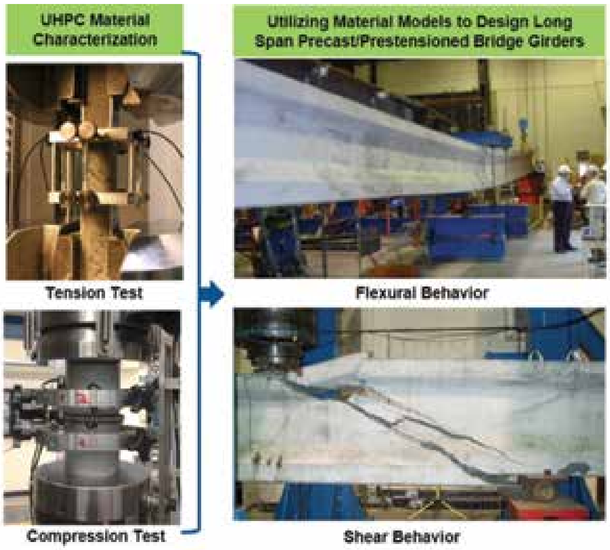
OBJECTIVE: To develop material testing standards, construction practices, and design methodologies for ultra-high performance concrete (UHPC), and to advance innovative structural applications that fully use UHPC's durability and performance characteristics.

ADVISER: **Ben 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 aims 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, post-cracking behavior in tension, compression, and ductility. This standardization will minimize variations in material data and foster the development of characteristic design models for UHPC. To pursue those goals, El-Helou is building 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 is also part of El-Helou's project. This effort is intended to validate that increasing the span range of concrete bridges can be achieved with UHPC.

IMPACT: El-Helou is taking part in FHWA efforts to develop and deliver a draft on UHPC for the *AASHTO LRFD Bridge Design and Construction Guide Specifications*. (LRFD is short for load and resistance factor design.) This work will support the American Association of State Highway and Transportation Officials' (AASHTO) 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.

ONGOING RESEARCH: El-Helou continues to assess the reliability of the current design approaches, as well as develop new design methodologies to recommend for the AASHTO draft. El-Helou is helping prepare for large-scale tests of UHPC girders that are planned for execution at FHWA's TFHRC, and he is using the findings to validate his proposed design methodologies.



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

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

Haber, Z. B., De La Varga, I., Graybeal, B. A., Nakashoji, B., & El-Helou, R. (2018). *Properties and behavior of UHPC-class materials*, Report No. FHWA-HRT-18-036, Federal Highway Administration, Washington, DC.

Graybeal, B., & El-Helou, R. G. (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.

El-Helou, R. G., & Graybeal, B. (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.

El-Helou, R. G., & 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.

Graybeal, B., & El-Helou, R. G. (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.

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–

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 Sivaneswaran,** 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.

Internal pavement response measure instrumentation of the Traffic Speed Deflectometer.

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.

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.

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

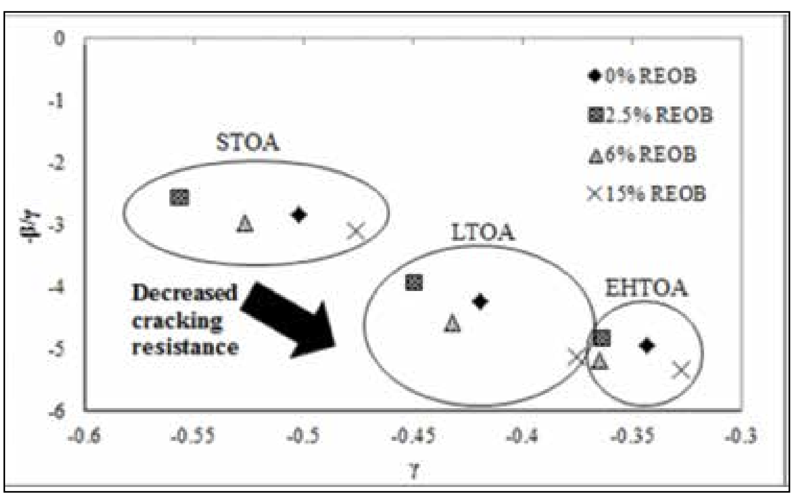
OBJECTIVE: To develop index parameters to relate material and structural parameters, identifying whether a mixture is prone to fatigue or thermal cracking.

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.

IMPACT: Mensching's research is expected to benefit FHWA's initiative on performance-based asphalt designs in multiple ways. The work will show how different asphalts perform based on temperature changes and fatigue stresses; it will expand national data about asphalt materials and soil structures for future research; it will expand the usefulness of Black Space diagrams to gauge the performance of asphalt mixtures and monitor pavement degradation; and it will generate a report to help highway departments and contractors adjust asphalt designs based on temperature, fatigue, and rutting performance.

ONGOING RESEARCH: Using continuum damage theory, the WesTrack study of regional differences in pavement materials continues to characterize the impact that volumetrics have on predicted asphalt performance. The Black Space diagram analysis of both binder and mixture with respect to the FHWA Accelerated Loading Facility sections is continuing, with high levels of reclaimed asphalt pavement and shingles.



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.

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.

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.*

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: **Ben 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 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.

Casting of beam splice connection.

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

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., Muttonni, 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/

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:

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

- 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.

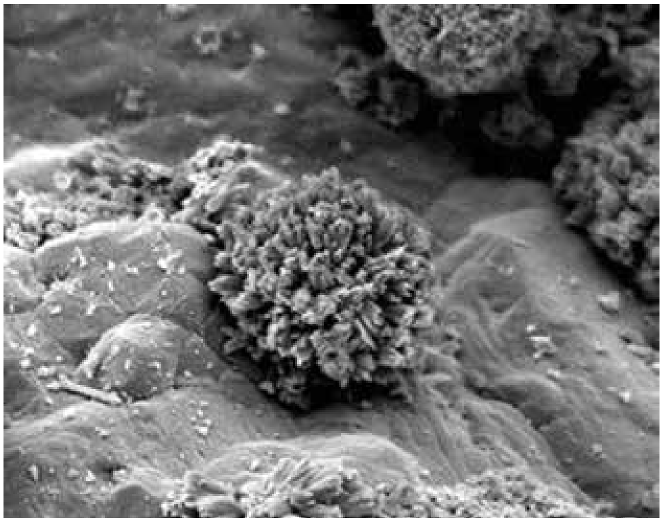
RESOURCES: Several publications and papers resulted from this RAP research. They are outlined below.

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).

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.



Nucleation of ettringite mineral in the interfacial transition zone.

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*.

PROJECT: **Developing New Vehicle–Tire and Contact Friction Models**

ASSOCIATE: **Emmanuel Bolarinwa**

SCHOOL: University of Birmingham

PERIOD: September 2013–September 2015

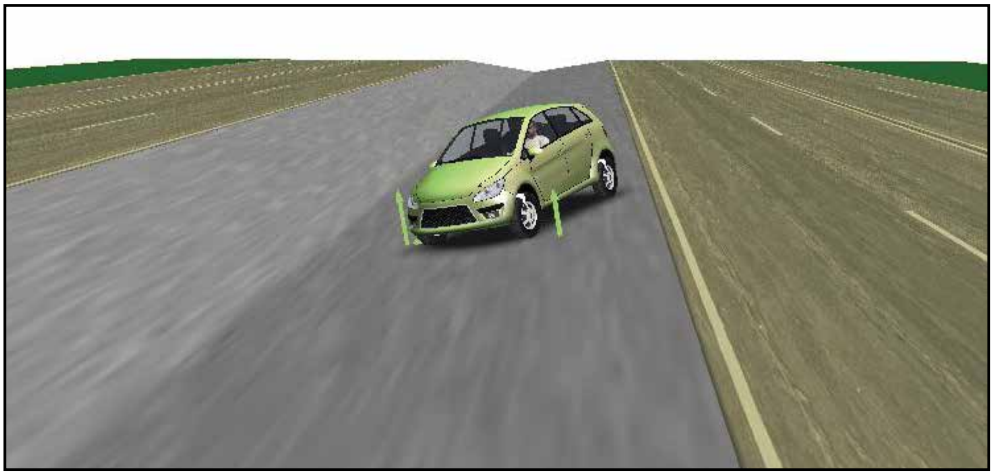
OBJECTIVE: To use a model-based approach for investigating the effect of tire–pavement contact friction on the safety performance of vehicles.

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.

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.

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

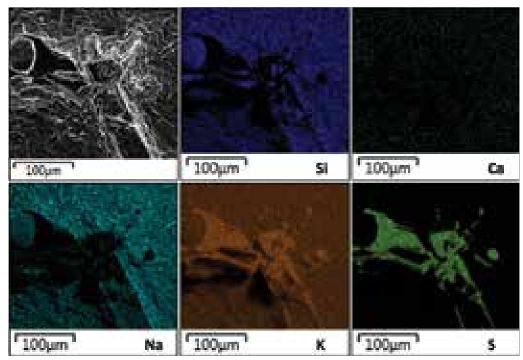
PERIOD: April 2010–April 2013

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.



Backscattered electron images of a potassium sulfate crystal formed inside of a silica gel in the interfacial transition zone.

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., Meininger, 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 Nano-technology 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.*

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

ASSOCIATE: **Mehdi Zamanipour**

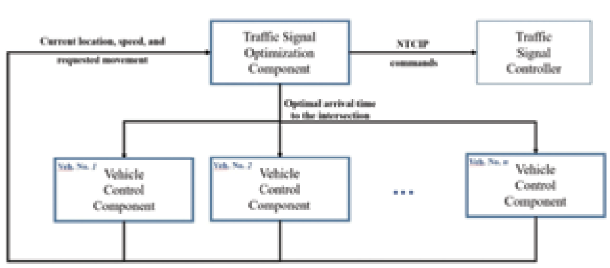
SCHOOL: University of Arizona

PERIOD: September 2016–

OBJECTIVE: To study the costs and benefits of deploying connected and automated vehicle (CAV) technology along signalized corridors and develop a tool to analyze the mobility and environmental benefits of deploying systems.

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

SUMMARY: Mehdi Zamanipour is evaluating the costs and benefits of deploying CAV technologies along signalized traffic corridors. His research examines two specific wireless communications applications—Multi-Modal Intelligent Traffic Signal Systems (MMITSS) and GlidePath. Developed under U.S. Department of Transportation (DOT) 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 an application called CAV Message Distributor, 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 is using the DOT-sponsored Research Data Exchange to calibrate baseline software models for traffic demand, signal t



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

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.

ONGOING RESEARCH: Zamanipour continues to develop and test the integrated signal and trajectory optimization model in the simulation environment. In addition, he will implement his model in testing intersections at FHWA's TFHRC and evaluate the benefits of the model.

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.

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.

Wolfgram, 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.

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

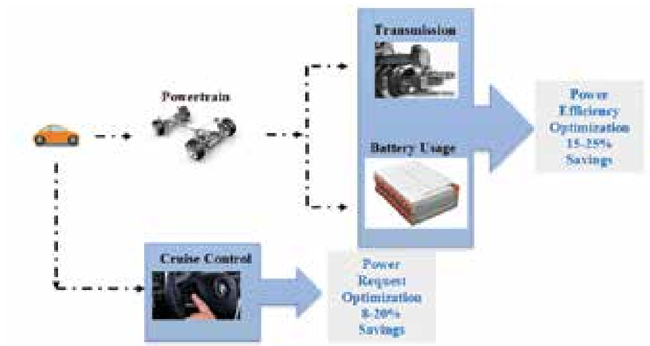
OBJECTIVE: To develop an algorithm for eco-cooperative adaptive cruise control (ECACC) that accounts for road topography to minimize fuel consumption and emissions while maximizing mobility.

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. This required identifying several stretches of highways with different topographies to serve as the prototype for a simulation test bed. The tests took into account 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.

ONGOING RESEARCH: Hu continues to develop a number of CACC controllers at this moment, including one that is robust against cyber attacks, one that cooperates with multiple signal controllers on a corridor, and one that includes humans in the control loop in order to improve the driving experience and reduce the hardware cost of enabling CACC. In addition, Hu is also developing a generic simulation platform incorporating vehicle dynamics for a more realistic evaluation of CACC's impact on traffic flow.



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.

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.

Connected Highway and Vehicle System Concepts

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

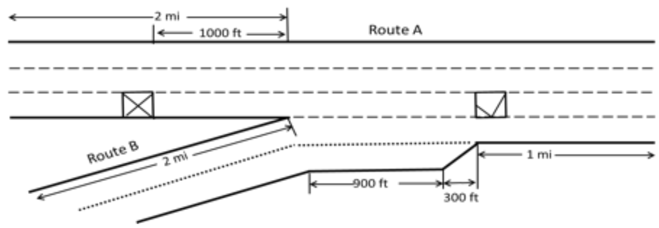
OBJECTIVE: To investigate the efficiency of dynamic merge control (DMC) strategy at freeway merge areas.

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 micro-simulation. *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*.

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.

ONGOING RESEARCH: Sarwar is currently continuing his research at the University of Buffalo.

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, 1*6, 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.

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

ASSOCIATE: Lin Xiao

SCHOOL: Hong Kong University of Science & Technology

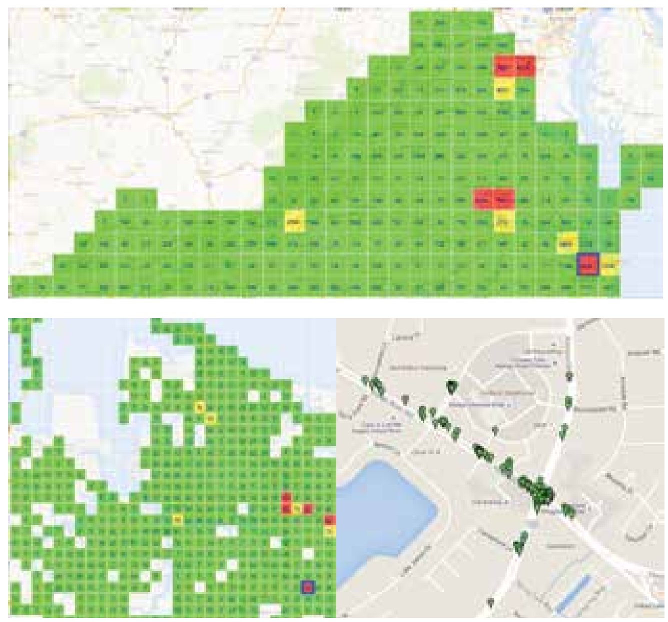
PERIOD: October 2015–June 2018

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 mi^2. The grids are ranked by crash frequency and crash cost. In Step 2, the selected grids are further partitioned into grids of 0.5 mi^2, 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 mi^2 and pick one for further analysis (Step 1); subdivide the highlighted grid in Step 1 into a grid of 0.5 mi^2 (Step 2); and identify a high-crash location.

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.

IMPACT: Xiao's research makes it easier for practitioners to identify and extract useful information from large SHRP 2 and other 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:

- 2-STEP, a tool for identifying high-crash locations based on multi-year, 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.

ONGOING RESEARCH: Xiao developed a series of software packages for data fusion, data analysis, and data mining that could have applications beyond his immediate research project.

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

Pan, D., Silverstein, C., Xiao, L., Caamaño, A., Zhang, W., & Hamdar, S. (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, Pittsburg, PA.

Zhang, W., & Xiao, L. (2018). *Vulnerable road user crash patterns in Orlando*. Presented at the 18th Chinese Overseas Transportation Association's International Conference of Transportation Professionals, Beijing, China.

Zhang, W., Xiao, L., Wang, Y., & Kelarestaghi, K. (2018). *Big data approach of crash prediction*. Presented at the 97th Transportation Research Board Annual Meeting, Washington, DC.

Wang, P., Wu, W., Wang, L., Xiao, L., Deng, X., & Li, M. (2017). A novel cooperative collision avoidance model for connected vehicles. *Transportation Research Record: Journal of the Transportation Research Board, 2645*, DOI: 10.3141/2645-16.

Kelarestaghi, K., Zhang, W., Wang, Y., Xiao, L., Hancock, K., & Heaslip, K. (2017). Impacts to crash severity outcome due to adverse weather and other causation factors. *Advances in Transportation Studies, 43*, 31–42.

Wang, P., Yu, H., Xiao, L., & Wang, L. (2017). Online traffic condition evaluation method for connected vehicles based on multisource data fusion. *Journal of Sensors, 2017*, Article ID 7248189, 11 pages.

Qu, X., Wang, S., Wang, T., Xiao, L., Yi, W., & Liu, Z. (2017). Mixed-integer linear programming models for teaching assistant assignment and extensions. *Scientific Programming, 2017*, Article ID 9057947, 7 pages.

Ren, Y., Wang, Y., Yu, G., Liu, H., & Xiao, L. (2016). An adaptive signal control scheme to prevent intersection traffic blockage. *IEEE Transactions on Intelligent Transportation Systems, 18*(6), 1519–1528.

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.

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.

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 microscopic traffic simulation to model characteristics and behaviors of traffic systems and to evaluate the performance of alternative designs. This 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 miniroundabout projects.

IMPACT: As of October 2014, at least one restricted-crossing U-turn and three miniroundabouts 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.

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

An aerial view of a two-cloverleaf highway interchange from a simulation video created by Nopadon Kronprasert.

ONGOING RESEARCH: Wei Zhang is continuing to conduct research on alternative intersection and interchange designs, building on Kronprasert's work. Zhang and Kronprasert are also collaborating on at least two more research papers.

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

Krause, C., Kronpraset, N., Bared, J., & Zhang, W. (2015). Operational advantages of dynamic reversible left-lane control of existing signalized diamond interchanges. *Journal of Transportation Engineering, 141*(5).

Zhang, W., & Kronprasert, N. (2014). The ABCs of designing RCUTs. *Public Roads, 78*(2), 9–13.

Zhang, W., & Kronprasert, N. (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.

Zhang, W., & Kronprasert, N. (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.

Zhang, W., & Kronprasert, N. (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.

Zhang, W., & Kronprasert, N. (2014). *Mini-roundabout case studies.* Presented at the Transportation Research Board's International Roundabout Conference, Seattle, WA.

Zhang, W., Kronprasert, N., & Gustafson, J. (2014). *Unclog local network congestion using high-capacity mini-roundabouts: A feasibility study.* Presented at the Transportation Research Board's 93rd Annual Meeting, Washington, DC.

Lochrane, T., Kronprasert, N., Bared, J., Dailey, D., & Zhang, W. (2014). Determination of mini-roundabout capacity in the United States. *Journal of Transportation Engineering, 140*(10).

Zhang, W., & Kronprasert, N. (2016). *System intersections—Concepts, simulation studies, and potential applications*. Presented at the International Conference on Transportation and Development 2016, Houston, TX. Available online: https://ascelibrary.org/doi/10.1061/9780784479926.020.

Zhang, W., & Kronprasert, N. (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. Available online: https://ascelibrary.org/doi/10.1061/9780784413869.020.

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.

The relationship between research methods and impacting factors. 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.

IMPACT: This research project is expected to demonstrate 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 will clearly show 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.

ONGOING RESEARCH: The second year of Romo's research concentrated on demonstrating applicability of fusing data from sources, such as driving simulator experiments and naturalistic driving studies, to gain an in-depth understanding about certain behaviors.

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.

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 years at the 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. Over 4 months, the research team (including Wang) presented the simulation results in multiple Web conferences, 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 multi-lane 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.

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., Xiao, L., Wang, Y., & Kelarestaghi, K. (2018). *Big data approach of crash prediction*. Presented at the 97th Transportation Research Board Annual Meeting, Washington, DC.

Kelarestaghi, K., Zhang, W., Wang, Y., Xiao, L., Hancock, K., & Heaslip, K. (2017). Impacts to crash severity outcome due to adverse weather and other causation factors. *Advances in Transportation Studies, 43*, 31–42.

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

Wang, Y., & Cheu, R. L. (2016). Operational impacts of implementing auxiliary lanes at isolated freeway off-ramps. *ITE Journal, 86*, 36–41.

Wang, Y., & Zhang, W. (2016). Analysis of roadway and environmental factors affecting traffic crash severities. *Transportation Research Procedia, 25*, 2124–2130.

Hancock, K., Zhang, W., Sardar, H., & Wang, Y. (2016). A two-step geo-grid screening process to identify locations for safety improvements. *Advances in Transportation Studies: An International Journal, special issue, 2*, 89–102.

Zhang, W., Hancock, K., Wang, Y., & Sardar, H. (2015). Estimate economic losses due to roadway crashes. *Proceedings of the 2015 Road Safety and Simulation International Conference.*

Zhang, W., Hancock, K., Wang, Y., & Sardar, H. (2016). Prioritize safety projects with confidence using two-step spatial screening. *Proceedings for ASCE International Conference on Transportation & Development.*

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

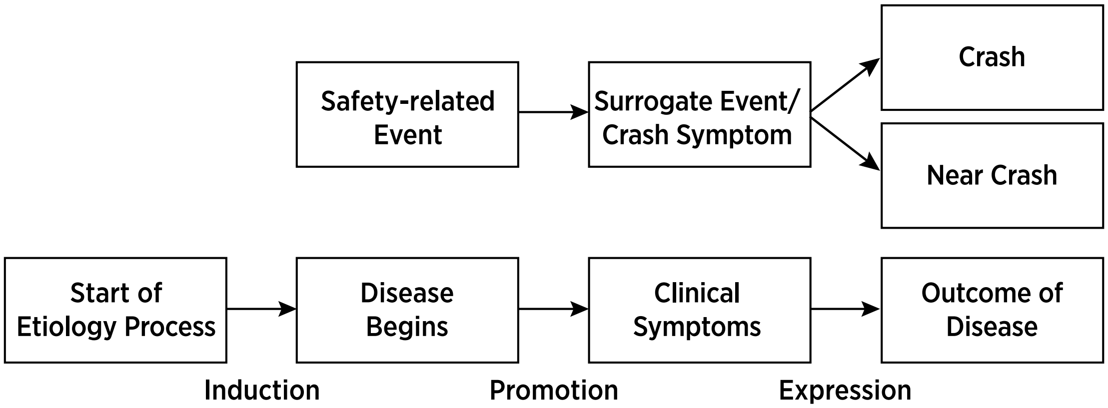
PERIOD: July 2012–June 2013

OBJECTIVE: To advance safety analysis using surrogate safety measures and improve the evaluation of intervention effectiveness.

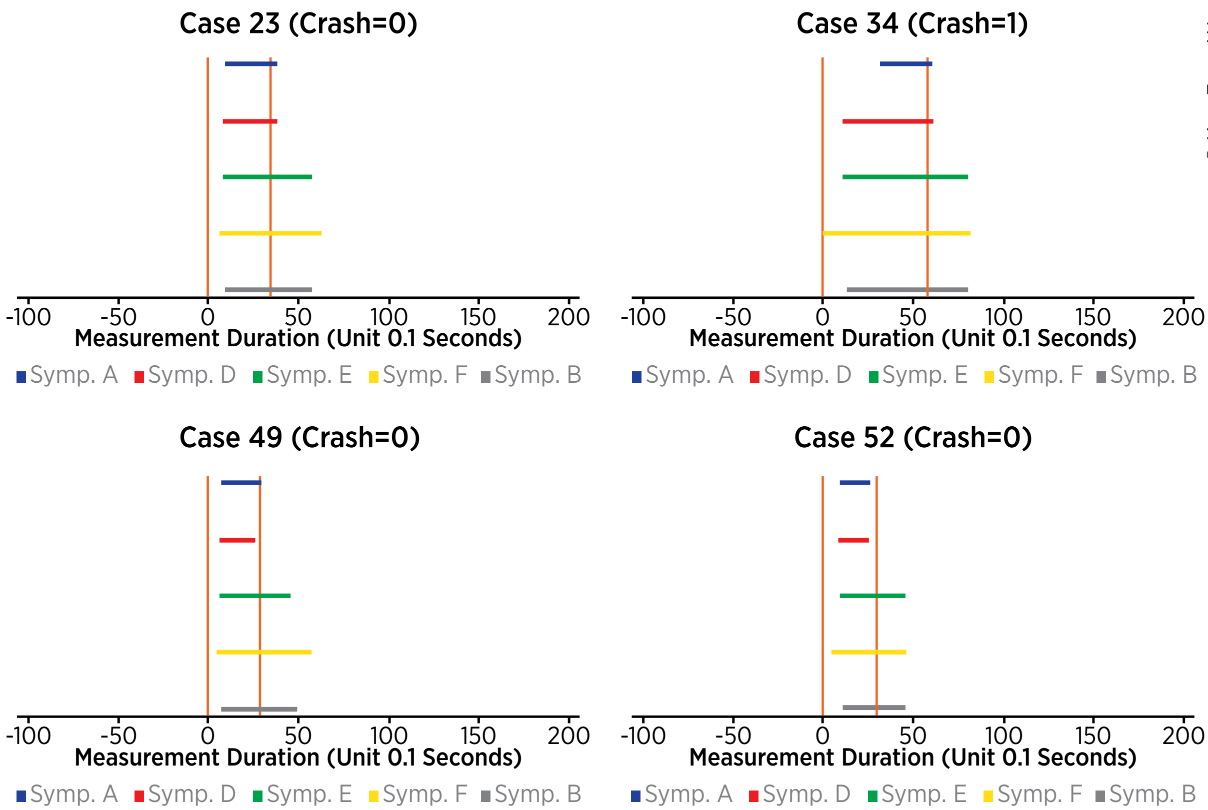
ADVISER: **Craig P. Thor,** FHWA Office of Safety Research and Development

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.

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.



A schematic that relates the crash progression process to the etiological process of disease progression.



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The crash symptoms (horizontal lines) as they compare to manual identification of a crash-related event (vertical red lines). This exhibits the potential of surrogate measures to predict safety-related events based on kinematic and environmental factors.

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.

PROJECT: **Air-Coupled Acoustic and Ultrasonic Arrays for Concrete Non-Destructive 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.

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**

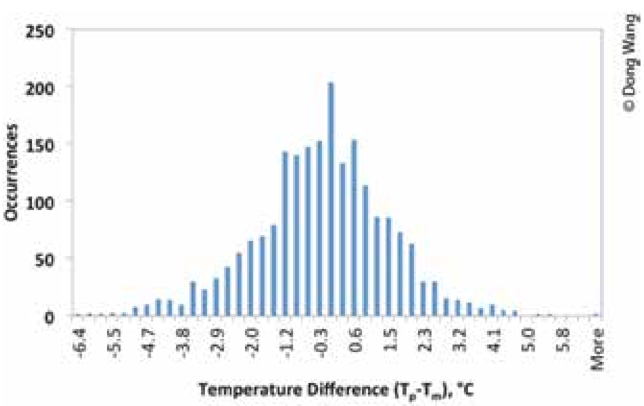
SCHOOL: University of Illinois at Urbana–Champaign

PERIOD: June 2011–May 2013

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

ADVISER: **Yan "Jane" Jiang,** FHWA Office of Infrastructure Research and Development

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 an d en vironmental lo adings. 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).

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.

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.

Getting Involved with the EAR Program

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

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

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