Accelerated Innovation Deployment (AID) Demonstration Project:

Increasing Pavement Performance through Pavement Foundation Design Modulus Verification and Construction Quality Monitoring

Final Report

October 8, 2021

ST-008

U.S. Department of Transportation
Federal Highway Administration

AID Demo
Accelerated Innovation Deployment

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TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
ST-008		

4. Title and Subtitle	5. Report Date
Increasing pavement performance through pavement foundation design modulus verification and construction quality monitoring	October 8, 2021
	6. Performing Organization Code
7. Author(s) Kera Gieselman (orcid.org/0000-0003-2322-2872) Melissa Serio, P.E. (orcid.org/0000-0002-6288-4062) David J. White, Ph.D., P.E. (orcid.org/0000-0003-0802-1167) Chris Brakke, P.E. (orcid.org/0000-0003-7442-2810) Pavana Vennapusa, Ph.D., P.E. (orcid.org/0000-0001-9529-394X) Tom Cackler, P.E., (orcid.org/0000-0003-4430-4826) Craig Swanson (orcid.org/0000-0003-0992-9476)	**8. Performing Organization Report No.**
9. Performing Organization Name and Address Ingios Geotechnics, Inc. P.O. Box 101 Northfield, MN 55057	**10. Work Unit No.** **11. Contract or Grant No.** ST-008
12. Sponsoring Agency Name and Address Iowa Highway Research Board Iowa Department of Transportation 800 Lincoln Way Ames, IA 50010 Federal Highway Administration 1200 New Jersey Avenue, SE Washington, DC 20590	**13. Type of Report and Period Covered** Final Report (July 15, 2019 to September 30, 2021) **14. Sponsoring Agency Code** ST-008

15. Supplementary Notes

Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. Abstract

The Iowa Department of Transportation (Iowa DOT) believes that an important step forward in improving pavement foundation construction quality as well as optimized pavement designs will be realized by implementing design modulus-based compaction verification and ensuring that the pavement design assumptions are met during construction. Proper compaction, and where needed, use of mechanical and chemical stabilization offer advantages for improving foundation material properties and performance. Modern technologies for field modulus verification, and field training, allows for rapid measurement, real-time construction compaction monitoring and modulus-based field control. To implement modulus-based field verification, as well as further advance e-Construction implementation efforts, the Iowa Highway Research Board (IHRB) with the Federal Highway Administration (FHWA) Accelerated Innovation Deployment (AID) grant pilot tested two innovative technologies that are not currently used in the State of Iowa: Modulus verification using real-time roller mapping technology (COMP-Score RT) and Automated Plate Load Testing (APLT). These technologies directly measure foundation support values in situ in terms of modulus of subgrade reaction (k-value) and resilient modulus (M_r) to verify pavement foundation design inputs as well as allow compaction monitoring and efficient data management. The work presented in this report and appendices builds on prior research investments, improved training, e-Construction efforts, and specification changes completed through Iowa Highway Research Board projects (TR 401, 461, 482, 492, 495, 501, 516, and 554, see http://publications.iowa.gov/) as well as Every Day Counts (EDC) initiatives. Iowa DOT developed a multi-year implementation plan to develop specification and provide training for statewide implementation. The work presented in this report is published at https://ideas.iowadot.gov/subdomain/ideas-main/end/node/3583?qmzn=iKFrYf.

17. Key Words		18. Distribution Statement	
in situ testing—modulus mapping—mechanistic QC/QA—MEPDG—pavement design—pavement foundation—resilient modulus—modulus of subgrade reaction—intelligent compaction—compaction monitoring		No restrictions.	
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 34	**22. Price** NA

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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Executive Summary

The purpose of this project was to deploy modulus-based field verification for pavement foundation layers, setup an e-Construction compaction reporting system, and independently calibrate results to in situ automated plate load testing (APLT) modulus measurement technology on five demonstration projects and develop the associated specifications to implement these technologies for pavement foundation design, construction, and performance monitoring.

In current pavement design methods and the new AASHTOWare™ Pavement ME Design guide, resilient modulus (M_r) values are used in both rigid and flexible pavement design, yet in situ modulus has not been measured or specified as part of the in situ pavement foundation quality inspection process. This leads to assuming design values from laboratory tests without field verification or selection of values based on empiricism. It has traditionally been difficult to perform direct modulus measurement on foundation layers in the field because test equipment does not simulate the correct loading conditions, or the measurement values cannot be directly linked to design values. In addition, there has not been a practical way to monitor the uniformity of foundation materials during construction.

With innovations in real-time roller compaction mapping and direct measurement of in situ stress-dependent resilient modulus and modulus of subgrade reaction (k-value), modulus-based assessment is now possible. Going into this project, the Technology Readiness Level (TRL) for APLT was rated as 9. Approximately 125 tests were able to be completed throughout the state in conjunction with a STIC project immediately preceding this project. When APLT is coupled with modulus verification roller mapping, it provides an efficient modulus mapping system to ensure the assumed pavement design values (such as AASHTO 1993, AASHTO 2015, and PCA 1984) are achieved during construction. Advancements with the next generation systems (e.g., output of verified modulus values) and real-time data reporting can now output design modulus values with a high degree of confidence (achieving $R^2 \geq 0.9$). The TRL level for modulus verification mapping was rated as 8 or above.

The equipment and analytical tools now exist and are commercially available to significantly advance pavement foundation performance by controlling field operations to ensure achievement of critical design assumptions. We believe that improved methods for in situ characterization (i.e., directly measuring engineering foundation parameters) are needed to improve pavement designs through proper calibration of the design equations, and this project will demonstrate the equipment, analytical tools, and provide training on the use of these technologies.

The scope of this project involved piloting five demonstration pavement foundation projects where APLT was used (in parallel with current inspection methods) to serve as primary calibration for the instrumented rollers. With input from industry stakeholders, we developed a set of pilot project specifications that link the project pavement design

of the foundation layers (subgrade and subbase layers) to the field quality control/assurance (QC/QA) measurements. We also developed guidelines for e-Construction compaction reports.

The use of these innovative technologies allowed the Iowa DOT to establish a link between pavement mechanistic design values (i.e., resilient modulus, k-value, and permanent deformation) for the critical foundation layers and the as-constructed conditions with near 100% spatial documentation of results. Longer-term the results will establish a new basis for understanding pavement performance as it relates to the as-constructed conditions where pavement distresses can be linked to geo-spatially referenced pavement foundation modulus measurements and the associated uniformity.

This project represents a major step forward at improving pavement foundation construction and inspection practices statewide and fulfils an important need as demonstrated by several prior projects completed in Iowa and nationally. Although specific to Iowa, this project should be of national interest for other state DOTs that are interested in better characterizing pavement foundation systems, integrating automation for field data analytics, and moving toward mechanistic pavement design and construction practices.

Provided in this report are appendices with all project data, a summary of a national survey supporting the need for implementation of new practices in this area, and a multi-year implementation plan to bring modulus verification mapping to state-wide quality assurance operations.

The work presented in this report with appendices is published online at http://publications.iowa.gov/ and https://ideas.iowadot.gov/subdomain/ideas-main/end/node/3583?qmzn=iKFrYf.

Introduction

The Iowa Department of Transportation (DOT) was awarded an Accelerated Implementation and Deployment (AID) Demonstration Grant for $700,000 in 2019 to support its goal of significantly increasing pavement performance by building high quality pavement foundations. In addition to the AID award, additional funding of $250,000 was committed through the Iowa Highway Research Board. The Iowa DOT believes that the next step forward in improving pavement foundation construction quality as well as optimized pavement designs will be realized by implementing real-time modulus-based quality assurance/verification to ensure that pavement design assumptions are met during construction.

ACCELERATED INNOVATION DEPLOYMENT (AID) DEMONSTRATION GRANTS

The Federal Highway Administration (FHWA) AID Demonstration Grants Program, which is administered through the FHWA Center for Accelerating Innovation (CAI), provides incentive funding and other resources for eligible entities to offset the risk of trying an innovation and to accelerate the implementation and adoption of that innovation in highway transportation. Entities eligible to apply include State departments of transportation (DOTs), Federal land management agencies, and tribal governments as well as metropolitan planning organizations and local governments which apply through the State DOT as subrecipients.

The AID Demonstration program is one aspect of the multi-faceted Technology and Innovation Deployment Program (TIDP). AID Demonstration funds are available for any project eligible for assistance under title 23, United States Code. Projects eligible for funding shall include proven innovative practices or technologies such as those included in the Every Day Counts (EDC) initiative. Innovations may include infrastructure and non-infrastructure strategies or activities, which the award recipient intends to implement and adopt as a significant improvement from their conventional practice.

REPORT SCOPE AND ORGANIZATION

This report documents the Iowa DOT's demonstration grant award results for *Increasing Pavement Performance through Pavement Foundation Design Modulus Verification and Construction Quality Monitoring* using real-time modulus mapping and e-Compaction reporting. The report presents details relevant to the employed project innovation(s), the overarching TIDP goals, performance metrics measurement and analysis, lessons learned, and the status of activities related to adoption of real-time modulus measurement technologies during pavement foundation layer construction as compared to conventional practice by the Iowa DOT. In addition to the project report, the following technology transfer activities were conducted and developed as part of the project:

- A technology brief was developed and is included in Appendix I.

- Technical working group meetings were conducted with stakeholders from the Iowa DOT, FHWA, local contractors, and local contractor associations.
- A field hands-on demonstration and training was conducted to personnel from the Iowa DOT and the contractor at one of the project sites.
- Training materials were developed for operators and engineers on how to use the modulus mapping technology and e-Compaction reporting web interface.

Appendices I to IX are attached to this report. Appendix I includes the technology transfer material developed for this project. Appendix II – User Satisfaction Survey – is included for template and is not applicable for this project. Appendix III includes a list of web resources used for this project. Appendix IV includes the cited references in this report. Appendix V acknowledges efforts by the Technical Advisory Committee (TAC), and the Technical Working Group (TWG) members. Appendix VI includes details on the Iowa DOT Implementation Plan. Appendix VII summarizes the national DOT survey findings and results. Appendix VIII describes the e-Construction reporting web interface and the contents. Appendix IX provides results from the demonstration project sites, and e-Compaction reports.

Project Overview

Direct measurement and verification of the design modulus of the pavement foundation layers has been limited in practice due to challenges with inadequate testing procedures and lack of practical ways to monitor the uniformity of foundation materials during construction. This project addressed these challenges by deploying and shadow testing modulus mapping and e-Compaction monitoring and reporting solutions on several active pavement foundation construction demonstration projects in 2019 and 2020 in Iowa. The results were used to directly compare with the assumed design modulus values. The use of independently outfitted and calibrated machines (with a certified professional engineering record), and the use of data processing and reporting tool without manual intervention allows for using the modulus mapping results for quality assurance (QA) by the DOT. This method differentiates from the traditional intelligent compaction (IC) technologies with index value measurements obtained from the Contractor owned machines/technology that cannot be used for QA (Conway 2019).

The products from this project included:

- deployment and field demonstrations of modulus mapping and automated plate load testing (APLT) technologies at multiple projects to document the as-constructed modulus values of the pavement foundation layers
- customization of a cloud-based modulus e-Compaction reporting tool for Iowa DOT, contractor offices, and field staff to document and share engineering reports in near real-time,
- development of effective communication tools (technical brief, webinars, and implementation guide) to promote training/rapid adoption, and

- development of an agency implementation plan and specifications for pavement performance monitoring for future projects constructed with modulus-based field design verification.

The implementation of *Pavement Foundation Design Modulus Verification and Construction Quality Monitoring* supports the TIDP/AID programmatic goals in several significant ways as summarized in Table 1.

Based on the lessons learned from this project, the Iowa DOT in collaboration with Ingios developed a detailed implementation plan that included developing special provisions for two pilot projects for the 2021 construction season. The 5-year plan addressed the education, training, and timeframe for transitioning from current practice to full statewide deployment of modulus-based construction requirements potentially by 2025.

Table 1. Summary of how Pavement Foundation Design Modulus Verification and Construction Quality Monitoring impacts FHWA's TIDP/AID Program Goals.

TIDP/AID Goals	Impact/Alignment with Project Outcomes
Improving Highway Efficiency	Enables more cost-effective pavement designs due to less risk/uncertainties by directly measuring and controlling engineering properties of the foundation support layers.
Improving Safety	Fewer traffic impacts and exposure of workers due to potentially reduced maintenance and repairs.
Improving Mobility	Increased pavement performance over time will reduce ownership cost thus enabling other system improvements.
Improving Reliability	Quality measurements of the pavement foundation at nearly 100% frequency greatly reduces chances of accepting non-conforming work.
Improving Service Life	Foundation related failures will be greatly reduced, resulting in significant improvement in service life.
Environmental Protection	Reduces future environmental impacts due to less maintenance and repairs with the associated reduction in traffic impacts.
Sustainability	Enables pavement foundations to be engineered to address current needs and be reused in the future.
Improving Quality	Highly reliable direct measurement of the engineering properties of the foundation layers enables pavements to perform as designed.
Reducing Project Completion/Construction Time	Data reports in real time enable more efficient construction operations and project acceptance. Eliminates potential rework of non-complying materials.

Project Details

BACKGROUND

The project involved deploying real-time modulus mapping technology that is calibrated with in situ direct measurements of modulus and e-Compaction reporting of the results in near real-time (within minutes). Modulus-based field assessment and geospatial mapping is needed to ensure that design assumed values for pavement foundations are met during construction. Near real-time automated analysis and reporting of the analyzed mapping results to the Contractor and Engineer through e-Compaction reporting is vital in making decisions to improve areas that do not meet the quality requirements.

Iowa DOT currently uses the PCA (1984) design method for rigid pavement design and AASHTO (1993) for flexible pavement design. The key design input parameter that characterizes the support of the pavement foundation is modulus of subgrade reaction (k-value) for rigid pavement design and resilient modulus (M_r) for flexible pavement design. Iowa DOT is in the process of calibrating and implementing the modern AASHTOWare™ Pavement ME Design guide (AASHTO 2018), in which stress dependent M_r is used in both rigid and flexible pavement design. Even though pavement design procedures have been modernized, verification of the assumed M_r or k-values in situ is currently not a part of the quality inspection/assurance process. The assumed design values are largely based on laboratory tests without field verification or selection of values based on empiricism.

Recent field testing performed as part of the Iowa DOT's State Transportation Innovation Councils (STIC) Incentive Projects (ST-003), which involved direct measurement of in situ modulus values during pavement foundation layer construction, documented that 11 out of 15 tests performed across the State of Iowa did not meet the design assumed values (White et al. 2019a). Field testing also showed evidence of significant non-uniformity, which is known to be one of the leading causes of premature failures in concrete pavements. It has traditionally been difficult to perform direct modulus measurement on foundation layers in the field because the traditional testing equipment does not simulate the correct loading conditions, or the measurement values are not directly linked to design values. In addition, there has not been a practical way to monitor the uniformity of foundation materials during construction.

With innovations in Automated Plate Load Testing (APLT) and modulus mapping technologies that demonstrate a high degree of statistical confidence, modulus-based assessment, direct measurement and verification of design inputs, and assessment on non-uniform support conditions is now possible. Combined with the measurement technology and near real-time reporting and dissemination of the results, timely decisions can be taken to implement corrective actions before it is too late. The equipment, the analytical tools, and the e-Compaction reporting tools to make such real-time modulus based assessments possible are now commercially available. These innovations have been demonstrated at other projects by Ingios for Minnesota DOT (White and Vennapusa 2017), Illinois Tollway Authority (Tutumluer et al. 2018, White et al. 2018), Colorado DOT (Carter et al. 2020), and Tennessee Valley Authority (White et al. 2017, White et al. 2019b).

To conduct field demonstrations of these innovations in the State of Iowa, the project team worked with the Iowa DOT and the Contractor personnel on eleven DOT and two County projects during the 2019 and 2020 construction season. Figure 1 shows the project locations, where the technologies have been deployed, and Table 2 summarizes additional information regarding each of the projects.

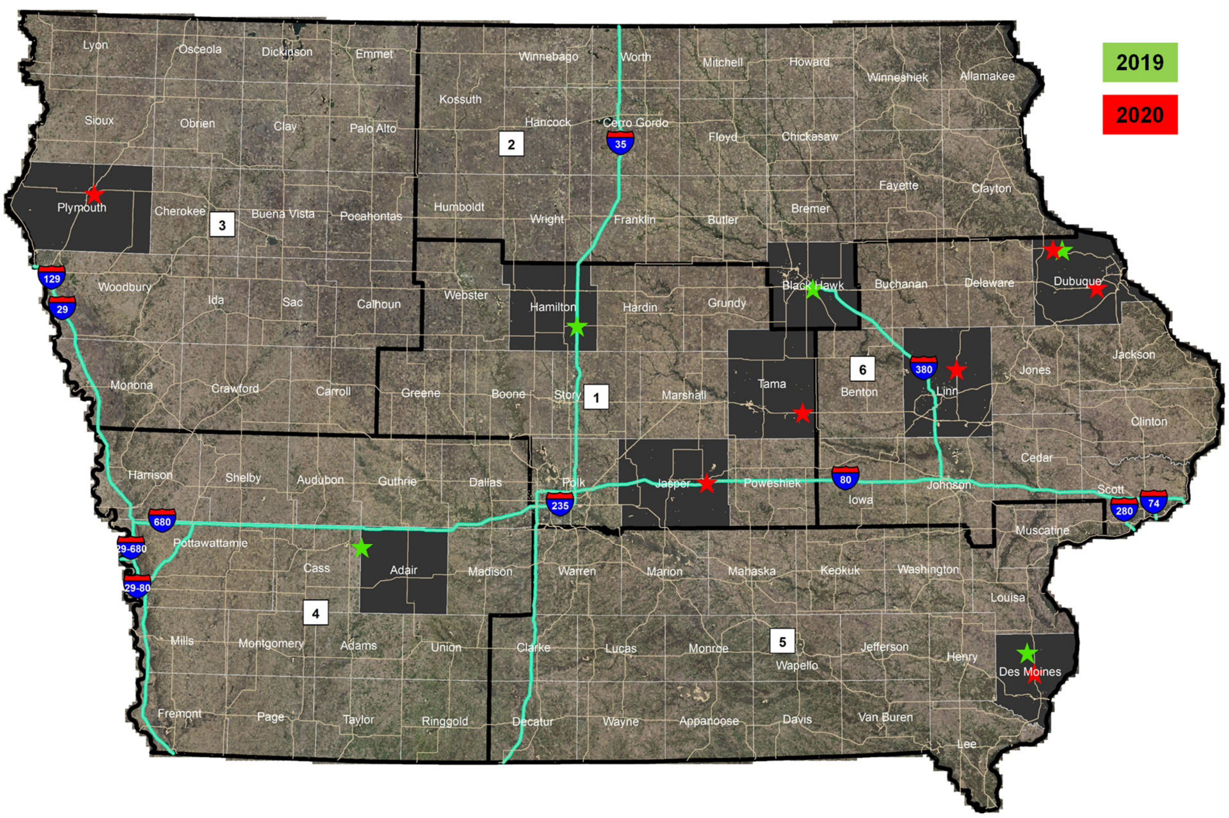


Figure 1. Project demonstration locations in 2019 and 2020.

Table 2. 2019 and 2020 Project Summary

County	Project Number	Contractor	Type of Project
2019 Demonstration Projects			
Blackhawk	NHSX-020-6(71)--3H-07	Cedar Valley	PCC Pavement
Hamilton	IM-035-5(111)133--13-40	CJ Moyna & Sons	PCC Pavement
Dubuque	HSIPX-052-2(120)--3L-31	CJ Moyna & Sons	PCC Pavement
Adair	LFM-LGG27--7X-01	County	Grading
Des Moines	L-P103GRADE--73-29	County	Grading
Des Moines	NHSX-061-2(62)--3H-29	Ames Construction	Grading
2020 Demonstration Projects			
Des Moines	NHSX-061-2(68)--3H-29	Streb Construction	PCC Pavement-New
Dubuque	NHSX-052-2(121)--3H-31	CJ Moyna & Sons	PCC Grade and Replace
Dubuque	NHSX-020-9(183)--3H-31	CJ Moyna & Sons	PCC Pavement-Grade and New
Jasper	IM-NHS-080-5(303)174--03-50	Peterson Contractors	PCC Pavement-Grade and New
Linn	NHSX-013-1(53)--3H-57	CJ Moyna & Sons	PCC Grade and Replace
Plymouth	NHSX-075-2(96)--3H-75	Peterson Contractors	PCC Grade and Replace
Tama	NHSX-030-6(191)--3H-86	Manatts	PCC Pavement-New

PROJECT DESCRIPTION

The purpose of this project was to deploy modulus mapping technology for construction quality monitoring and demonstrate e-compaction reporting, with the main objective of increasing pavement performance. The use of real-time modulus mapping and e-Compaction reporting technologies for quality assessment of pavement foundation layers is a significant leap forward from the current state of the practice in Iowa. The current state of the practice involves either moisture or moisture and density control with testing at randomly selected test point locations and is limited to only the soil subgrade material. This practice does not provide adequate statistical assessment of the foundation layers and the conventional measurements do not relate to the design assumed values. Geospatial mapping of design-modulus values with 100% coverage of the constructed pavement foundation layers ensures that design assumptions are met during construction. Longer-term, the geospatially referenced foundation layer modulus mapping results will establish a new basis for understanding pavement performance with a link between the as-built conditions and any future pavement distresses.

Demonstration Projects and Performance Measures

To demonstrate the innovations, the technologies have been deployed for field demonstrations to a total of thirteen sites as summarized in Table 2. At each of the project sites, Ingios Engineers collected the relevant project details, foundation layer design inputs, aerial imagery, and line drawings. A vibratory smooth drum compactor outfitted with Ingios COMP-Score® RT kit, which provides the modulus-mapping results, was deployed (Figure 2). APLT was deployed along with the outfitted roller to perform field calibration testing to measure M_r and k-values (Figure 3). Additional field testing involved dynamic cone penetrometer testing to assess layer thicknesses and penetration index values with depth, and field drainage testing to assess permeability of granular subbase materials. A site-specific testing and sampling plan was designed based on the project and material site conditions, and project-specific objectives developed in coordination with Ingios and the Iowa DOT personnel. Field testing was conducted on a variety of pavement foundation layer materials including select subgrade (cohesive), subgrade treatment (e.g., cement treated subgrade, special backfill, over excavation and replacement with modified subbase), granular subbase, modified subbase, and macadam stone base layers. Materials were also collected from each of the project sites for additional laboratory characterization and testing.

Field testing was conducted at 100 test locations to measure the in-situ k-value and 38 test locations to measure M_r value. Data collected for a wide range of material and site conditions from multiple project sites provided a robust dataset for state-wide calibration of the modulus mapping results. Professional Engineering calibration records based on the state-wide data, test and data analysis methods, details from each project, field and laboratory testing results, and e-Compaction reports generated from each project site are included in Appendix IX.

A plot of k-value versus permanent deformation (δ_p) at the end of the static plate load test is shown in Figure 4. The results indicated that only 36 out of the 100 test measurements met the design assumed values. These results further emphasize the importance and need for real-time detection of areas not meeting the minimum design criteria during construction so that necessary corrective actions could be taken. An example of Professional Engineering documentation of the pavement foundation material specific calibration record developed from the project data is shown in Figure 5. Additional calibration records for other materials and measurements are included in Appendix IX. The material-specific calibration records produced from this project demonstrated high statistical confidence in the results with coefficient of determination (R^2) ≥ 0.9.

The modulus mapping results are auto-processed to generate e-Compaction reports per the format established for this project. Ingios developed the auto-generation and email alert messaging, so the reports are available in near real-time during construction (within 2-5 minutes after mapping is completed). A cloud-based e-Construction web interface developed by Ingios – COMP-Score® CONNECT – is used to process, view, disseminate and archive the results. A screenshot of the e-Construction web interface is shown in Figure 6. Key features of the e-Construction web interface are as follows and additional details are included in Appendix VIII:

- Near real-time data processing and e-Compaction report generation
- Highly formatted reports, designed specifically to meet IA DOT specifications

- Review functionality allows users to set status and communicate with project stakeholders directly within an e-Compaction report
- Digital image upload allows you to insert images directly into an e-Compaction report
- Scroll through completed maps as a visual quick reference
- Track key metric performance over time on a project with control charts

The e-Compaction reports generated from each of the demonstration project sites are included in Appendix IX as part of the project test results. The report pages include the following:

- Mapping Summary with key parameter statistics.
- Quality Analysis Summary – Resilient Modulus or Modulus of Subgrade Reaction or Both, with the following compaction quality criteria:
    - *Compaction Quality Index (CQI)*, which is a relative compaction index based on the percentage of the geospatial area that meets the minimum target values and accounts for the uniformity of compaction. The default minimum target CQI is 95% using a uniformity weight factor of 50%.
    - *Percent Passing Target Values* calculated based on the number of geospatial grid points from the mapping output that meet or exceed the minimum reference modulus value for the selected material. The default target %_Passing TV ≥ 80%.
    - *Coefficient of Variation (COV)* calculated based on the modulus values reported at each grid point of the mapping area. The default target COV is ≤ 20%.
    - *Percent Blob Area r*epresents the percentage of the area within the map area that has been identified as a prioritized contiguous area that is ≥ 200 sq. ft, with measurement values < target values (the 200 sq. ft. area requirement can be adjusted based on project conditions).
- Geo-referenced color-coded mapping results overlaid on an aerial image:
    - Resilient Modulus or Modulus of Subgrade Reaction Maps
    - Delta Resilient Modulus or Modulus of Subgrade Reaction Maps – the delta value represents measured modulus minus target modulus
    - Blobs-Delta Resilient Modulus or Modulus of Subgrade Reaction i-Score Maps – with summary statistics of the total area and the boundaries that require improvement to meet the established target values.
    - Pass Count Map
    - Elevation Map (where real-time kinematic global positioning system [RTK-GPS] measurements are available, otherwise map shows gray coloring)
    - Material Identification Map
    - Digital images

The “blob” map (see Figure 7) included in the e-Compaction report highlights, identifies, and prioritizes the statistically contiguous areas that need improvement (i.e., not meeting the design values). It is a critical map that is auto generated as an outcome of the analysis of the modulus mapping results, that can then be used by field engineer in the decision-making process in real time.

Figure 2. Vibratory smooth drum roller outfitted with modulus-mapping technology (insert: touch screen monitor for selection and viewing of results in real-time).

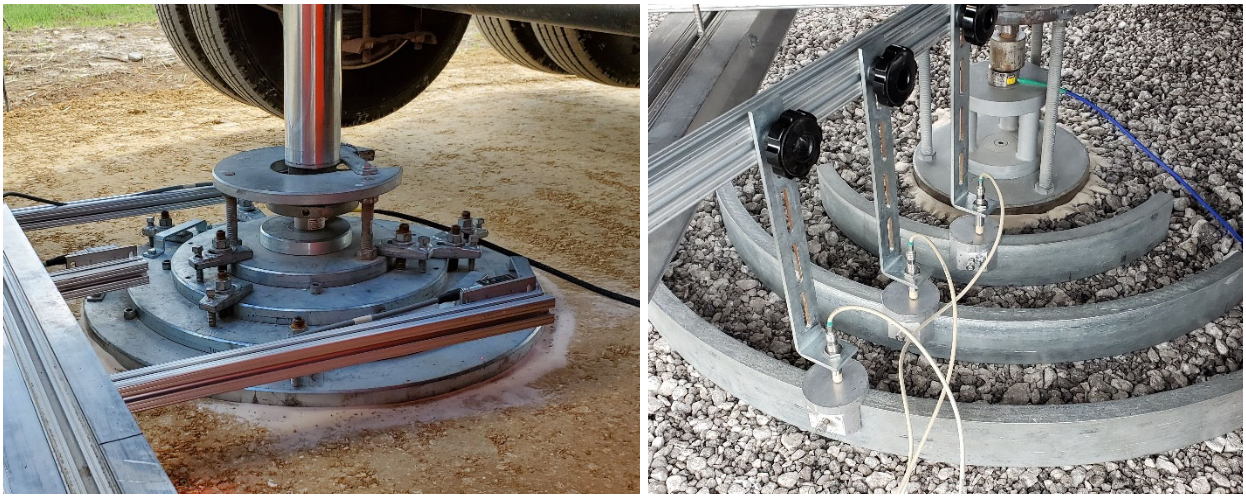


Figure 3. Automated Plate Load Testing trailer (top) with plate setups for measurement of k-value using static plate load test with 30 in. diameter loading plate (bottom left) and a M_r using cyclic plate load test with 12 in. diameter loading plate (bottom right).

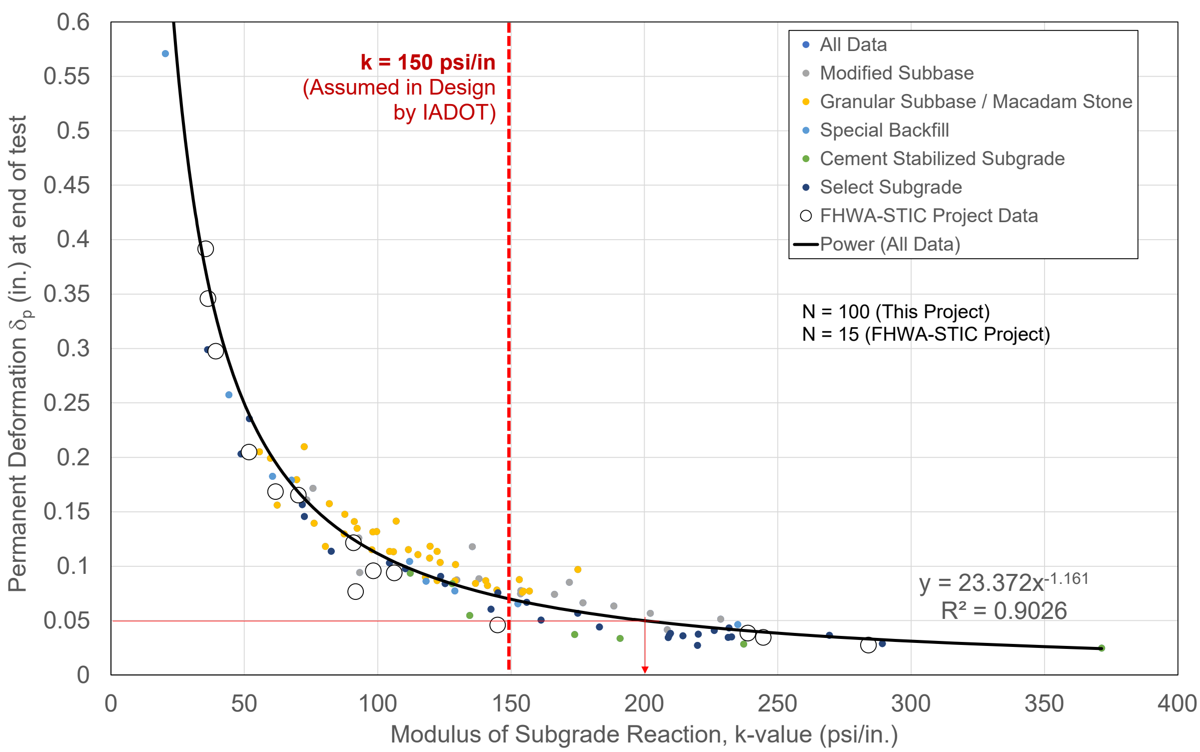


Figure 4. k-value versus permanent deformation (δ_p) at the end of test from field test measurements at all project sites

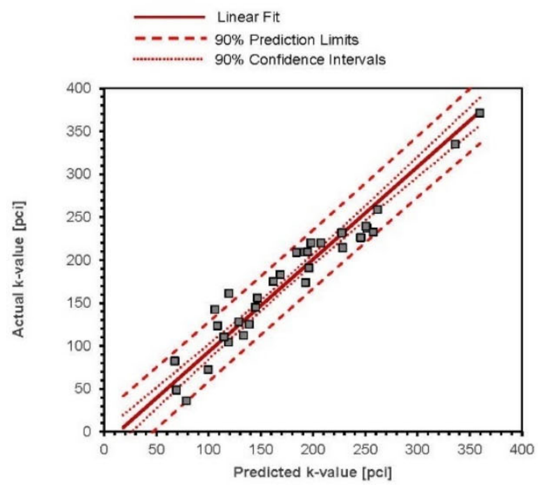
COMP-Score® RT – Calibration Record

Machine	CS56 vibratory smooth drum roller (ID: CAT0CS56JFCS00210); Sensor ID: SN3927
Date(s):	10/23/2019 to 09/20/2020 — Tested By: HG, CV, DW, PV — CAL ID: IA-AID_2020_k-SG
Notes/ Comments:	Modulus of subgrade reaction value (k-value) for the first loading cycle at 10 psi applied stress with plate bending correction and correction for seating, per AASHTO T222. Field testing conducted at 32 test locations on compacted select subgrade (cohesive) and compacted cement stabilized subgrade. Roller operated at high frequency (f = 31.25 Hz), low amplitude vibration setting, and full speed. Note: Multiply k x 19.79 to calculate Elastic Modulus (E) [Poisson's ratio of 0.4 and shape factor of π/2 for rigid plate over cohesive material]

		Selected Stress, σ = 10 psi		
Test Point ID	Profile	Actual k-value [pci]	Pred. k-value [pci]	RT Reported k-value [pci]
US52_pt1	CSS	173.9	192.7	164.9
US52_pt2	CSS	190.9	196.1	167.9
US52_pt3	CSS	237.3	251.4	217.0
US52_pt4	CSS	112.2	133.4	112.3
US52_pt5	CSS	127.9	128.9	108.3
US52_pt6	CSS	371.4	359.5	312.8
I80_pt1	SG	48.8	69.1	55.3
I80_pt2	SG	36.2	78.7	63.8
US13, pt1	SG	259.0	261.6	226.0
US13, pt2	SG	335.1	336.1	292.1
US13, pt3	SG	231.7	227.4	195.7
US13, pt4	SG	125.3	138.8	117.1
Hwy75_pt1	SG	209.3	190.6	163.0
Hwy75_pt2	SG	183.1	168.5	143.5
Hwy75_pt3	SG	208.9	184.1	157.3
Hwy75_pt4	SG	219.9	198.0	169.6
Hwy75_pt5	SG	142.5	106.0	88.0
US30A_pt3	SG	145.1	144.8	122.5
US30B_pt1	SG	72.5	99.4	82.2
US30B_pt2	SG	220.2	207.6	178.1
US30B_pt3	SG	175.0	161.7	137.4
US30B_pt4	SG	104.4	118.8	99.4
US30B_pt5	SG	110.4	114.5	95.6
US61_pt1	SG	155.8	146.5	124.0
US61_pt2	SG	209.7	194.6	166.6
US61_pt3	SG	232.7	257.6	222.5
US61_pt4	SG	226.2	245.6	211.8
US61_pt5	SG	239.5	250.5	216.1
US61_pt6	SG	123.6	108.4	90.2
US61_pt7	SG	161.2	119.4	99.9
US61_pt8	SG	214.4	228.4	196.5
US61_pt9	SG	82.5	67.7	54.0

SG - Select cohesive subgrade; CSS - Cement stabilized cohesive subgrade.

Reported k-value = (1-%SE) * Predicted k-value - Δk-value



Regression Statistics

N	32
R^2	0.933
R^2(adj.)	0.928
RMSE	20.1 psi/in.
%SE*	11.3%
F-value	202.12
p-value	<0.0001

*Percent Standard Error (%SE) in prediction relative to mean

Regression Equation

Actual k-value = 1.000 x RT Pred. k-value + 0

Δk-value 6 psi/in.

SUMMARY STATISTICS	Actual	Predicted	Reported	
Minimum:	36.2	67.7	54.0	psi/in.
Maximum:	371.4	359.5	312.8	psi/in.
Mean:	177.7	177.7	151.6	psi/in.
Median:	179.1	176.3	150.4	psi/in.
Standard Deviation:	75.1	72.5	64.3	psi/in.
Coefficient of Variation:	42%	41%	42%	

Signature: *Pavana Vennapusa*

Typed Name: Pavana Vennapusa, Ph.D., P.E.

Date: 4/22/2021 License # P21991

I hereby certify that this plan, specification, or report was prepared by me or under my direct supervision and that I am a duly Licensed Professional Engineer under the laws of the state of Iowa.

COMP-Score® RT – Calibration Record

Project Name: Iowa TDIP-AID Demonstration Project
Project ID: SIA-00003
Location: Multiple Project Sites, Iowa

ingios GEOTECHNICS

Figure 5. Example calibration record

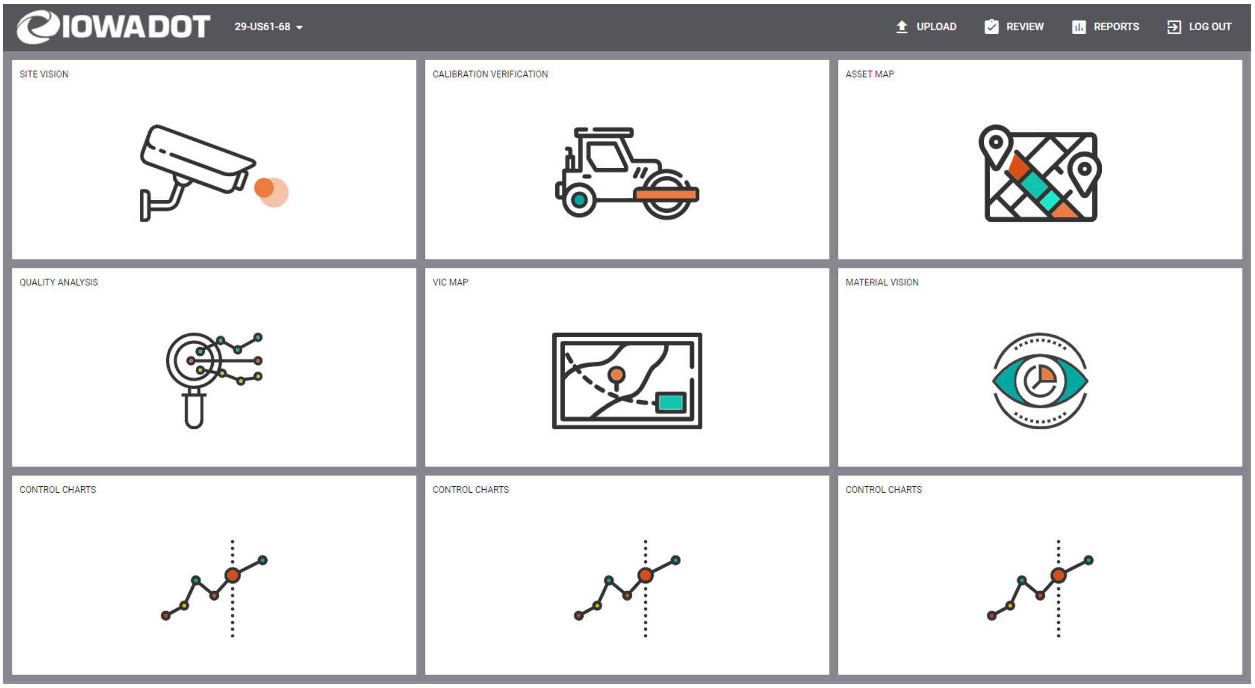
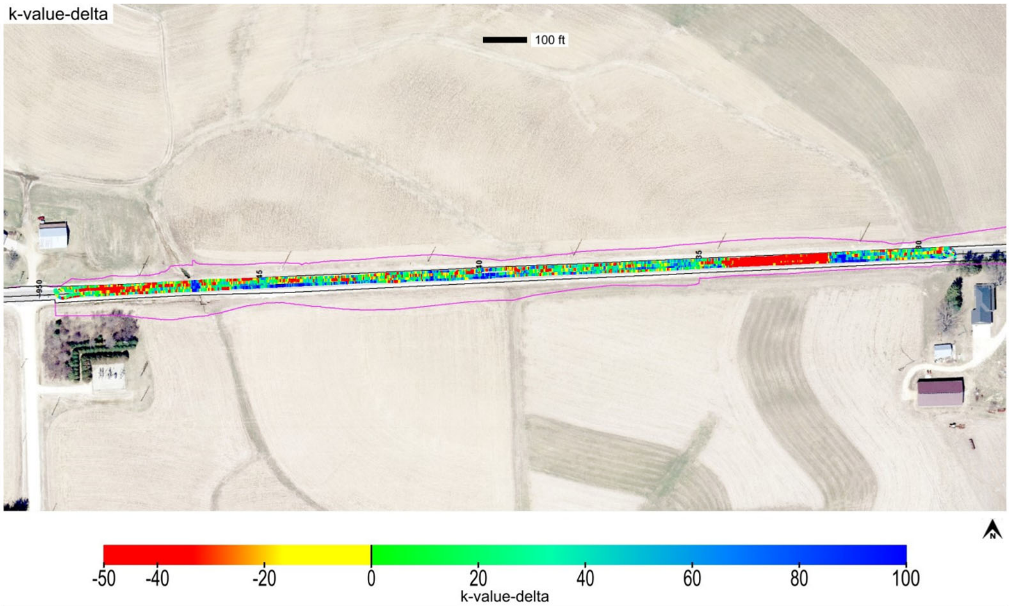


Figure 6. COMP-Score CONNECT e-Construction reporting web-interface.

E-Compaction Report

Map ID: iadot_31-us52_cs56-fcs00210_2020_08_12_114345a

Parameter	Measured	% Passing	CQI	CI	Calc. TV	min.	avg.	max.	std. dev.	cov(%)	min.-delta	avg.-delta	max.-delta
k-value	Yes	58	70.31	0.46	150	35	156.3	370	55.28	35.38	-115	6.3	220



E-Compaction Report

Map ID: iadot_31-us52_cs56-fcs00210_2020_08_12_114345a

min. area(ft^2)	# of blobs	blob area(ft^2)	% of map	lower bound-tv	upper bound-tv
200	12	14897	31.92	none	0

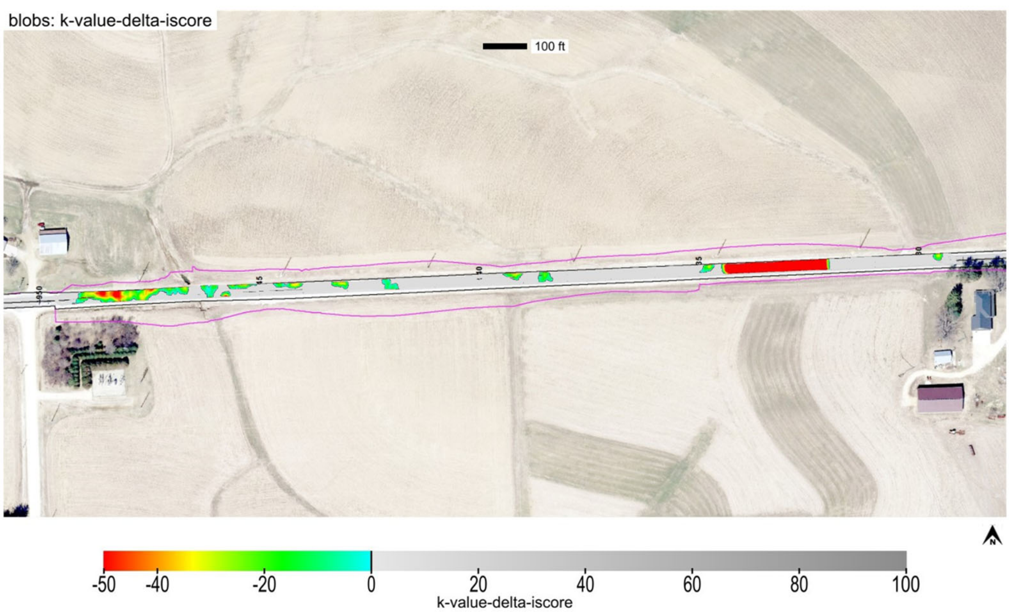


Figure 7. Example delta k-value and "blob" area map highlighting areas that do not meet the design assumed target k-value – US52 Dubuque Project.

Geo-spatially referenced modulus mapping results with 100% coverage from this project allowed additional analysis of the results to assess and create pavement design life maps. An example of design life maps from one of the project sites (US20) is presented in Figure 9. The maps are presented as delta design life (calculated as assumed design life [40 years] minus the calculated design life in Figure 9. The design life was calculated for PCC pavement, using the measured k-value and assuming typical design input values for the pavement layers and traffic, using the AASHTO (1993) rigid pavement design procedure. The maps are presented with consideration of loss of support (LOS), that is associated with differential movement/gaps generated because of permanent deformation (δ_p). For PCC pavements, a differential $\delta_p \geq 0.05$ in. is typically considered critical to induce fatigue failure (Birkhoff and McCullough 1979).

A rational approach for engineering an optimized solution for pavements is through economic analysis of the total cost. Costs during the life of a pavement are the sum of engineering, contract administration, construction, quality inspection services, maintenance, user, and rehabilitation. Offsetting total cost is the reusable/salvage value of the pavement at the end of its design life. Life cycle cost analysis (LCCA) provides a method for evaluating the total economic worth considering future costs associated with alternative pavement types and foundation support conditions. LCCA is considered good practice for network level analysis, and particularly beneficial for project segments considering alternative solutions.

The analytical LCCA method determines the net present value (NPV) of alternatives where the cost computed is the discounted monetary value of the benefits minus the costs.

$$NPV = Intial\ Cost + \sum_{k=1}^{N} Rehabilitation\ cost_k \left[\frac{1}{(1+i)^{n_k}}\right] - Salvage\ Value$$

where i = discount rate, n = year of expenditure

Although LCCA is often emphasized for comparison of different pavement materials, the quality of the pavement foundation layers is the primary variable considered herein as a key factor in pavement longevity and NPV comparisons.

Pavement foundations layers are the aggregate base and subgrade materials down to a depth of about 3 ft below bottom of pavement. The pavement foundation layers are designed to serve important functions of providing sufficient stiffness (measured in terms of M_r or k-value) to limit strain in the payment layer, providing uniformity (measured using spatial statistics) to minimize stress concentrations in the pavement layers, providing near-linear-elastic behavior (measured in terms of permanent deformation under traffic loading) to maintain uniform contact with the pavement, and providing adequate drainage (measured in terms of the time to drain water) to minimize erosion, freeze-thaw softening, and other material distress problems.

Using Ingios COMP-Score CONNECT data analytics, the as-constructed pavement foundation layers are analyzed in terms of pavement life considering stiffness, uniformity, and susceptibility to permanent deformation (Loss of support, LOS). The utility of linking LCCA with COMP-Score CONNECT (CSC) spatial mapping is that by analysis of the total cost incurred for the life of a pavement system, a rational decision of alternative options is available (i.e., spend more money now on higher quality pavement foundation versus less money now for a comparatively lower quality system but higher maintenance costs).

Considering that high quality pavement systems are built from the ground up and financial savings are realized in terms of prolonging pavement ride quality, minimizing pavement structural defects, and reducing user costs, the following example analysis was developed for discussion with the technical advisory group.

Example:

For a design analysis period of 40 years, there are two alternative solutions. No differences were applied to user costs or salvage costs. Baseline design initial cost: $18.0 million; cost to reconstruct after 40 years: $9.0 million.

- Alternative 1 (standard design + CSC): initial cost: $18.2 million; cost to reconstruct after 40 years: $9 million; maintenance cost applied at half of life:
- Alternative 2 (standard design + CSC + stabilization improvements): initial cost: $18.5 million; cost to reconstruct after 50 years: $9 million; maintenance cost applied at half of life.

Which alternative should be selected?

Solution:

The cost liabilities and savings delivered to a pavement system is presented below in Table 3 for an Iowa DOT project using COMP-Score CONNECT modulus verification roller mapping. The in situ spatial record of a segment of the project is shown in Figure 8 in terms of pavement service life maps from measurement of the as-constructed pavement foundation modulus (loss of support, LOS = 2) and the AASHTO pavement design framework.

Although the pavement design life for this segment is 40 years, the calculated as-constructed pavement life is about 31.2 years (considering LOS = 2).

Comparing Alternative 1 to the design life, the NPV derived benefit difference = $(773,460).

Alternative 2 though with higher initial cost due to the investment in COMP-Score CONNECT and contractor improvements (e.g., added compaction where needed, geogrid, cement stabilization) to deliver a 50-year design life, the resulting benefit is $558,188.

Therefore, alternative 2 has the lowest LCCA and should be considered for selection. Further, the difference in NPV from the current condition (Alternative 1, LOI =2) to the improved condition (Alternative 2) is therefore $1,331,648. Even with an estimated $500,000 upfront investment in the COMP-Score CONNECT solution + contractor improvements (~25,000 SY cement stabilization or 100,000SY geogrid stabilization), the benefit is 2.7x the initial investment.

Table 3. Summary of net present value (NPV) for alternative pavement foundation solutions.

Pavement Foundation Case	Average Design Life	NPV	Benefit
As-constructed k-value (LOS =2), moderate permanent deformation	31.2	$22,839,823	$(773,460)
Alt 1: COMP-Score™ CONNECT solution per Iowa DOT design requirement k-value (+$200k)	40 (per standard design)	$22,066,363	$-
Alt2: COMP-Score™ CONNECT solution and stabilization improvements (+$500k)	50	$21,508,175	$558,188

Benefits derived from vehicle operating costs, user delay costs, and crash costs are excluded. Benefits from salvage value excluded.

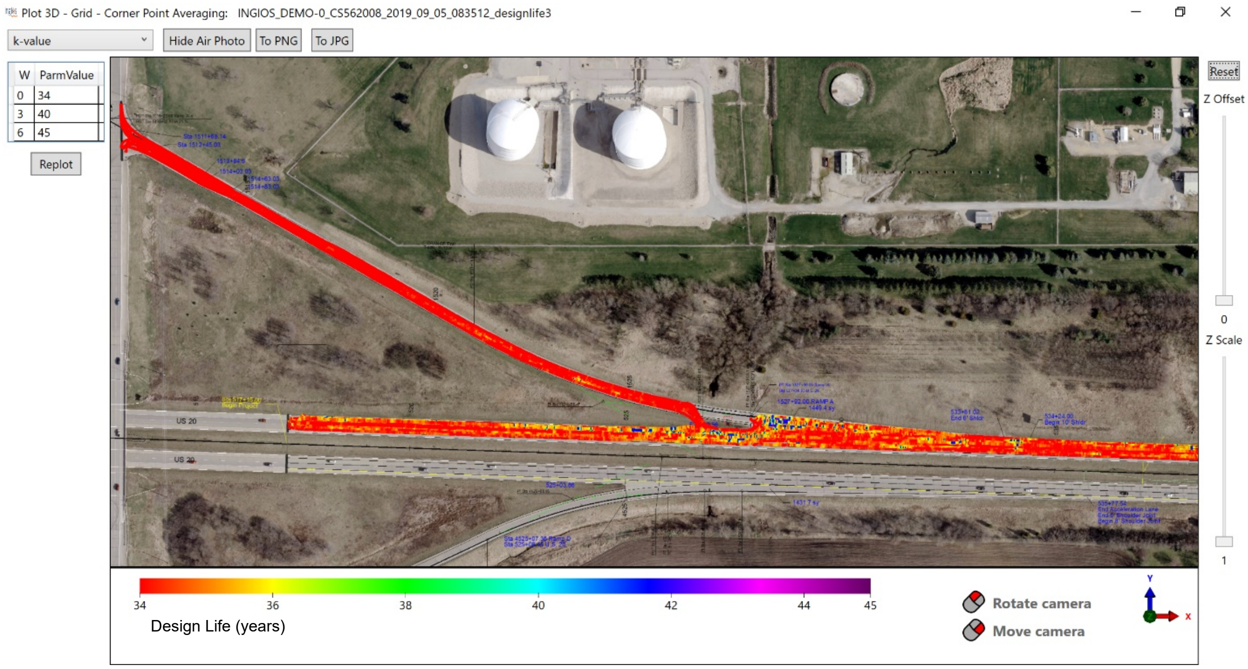


Figure 8. COMP-Score Map: As-constructed direct measured design life (average design life = 31.2 years, LOS = 2, moderate deformation)

By implementing the new workflow processes and quality requirements using modulus mapping and e-Construction reporting, results demonstrate that the pavement performance can be significantly increased by ensuring that the design-assumed values are met during construction. This improved performance can reduce unwanted maintenance costs and related traffic closures. Due to these, the life cycle ownership costs are reduced while providing greater safety to the public. Key benefits identified through discussion with our technical working group are summarized as follows:

1. Audit ready system (real-time documentation and history)
2. Optimized compaction (efficient roller patterns/improvements)
3. Reduced risk (of building poor quality) (future asset management tool/input)
4. Improved QC/QA inspection (intelligent analytics)
5. Minimized construction delays (data driven)
6. Improved safety (people off grade)
7. Data as asset (less risk on bid items in future)
8. Cost/value: LCCA (NPV analysis showing value, needs to drive sustainable pavement solutions with extended life).

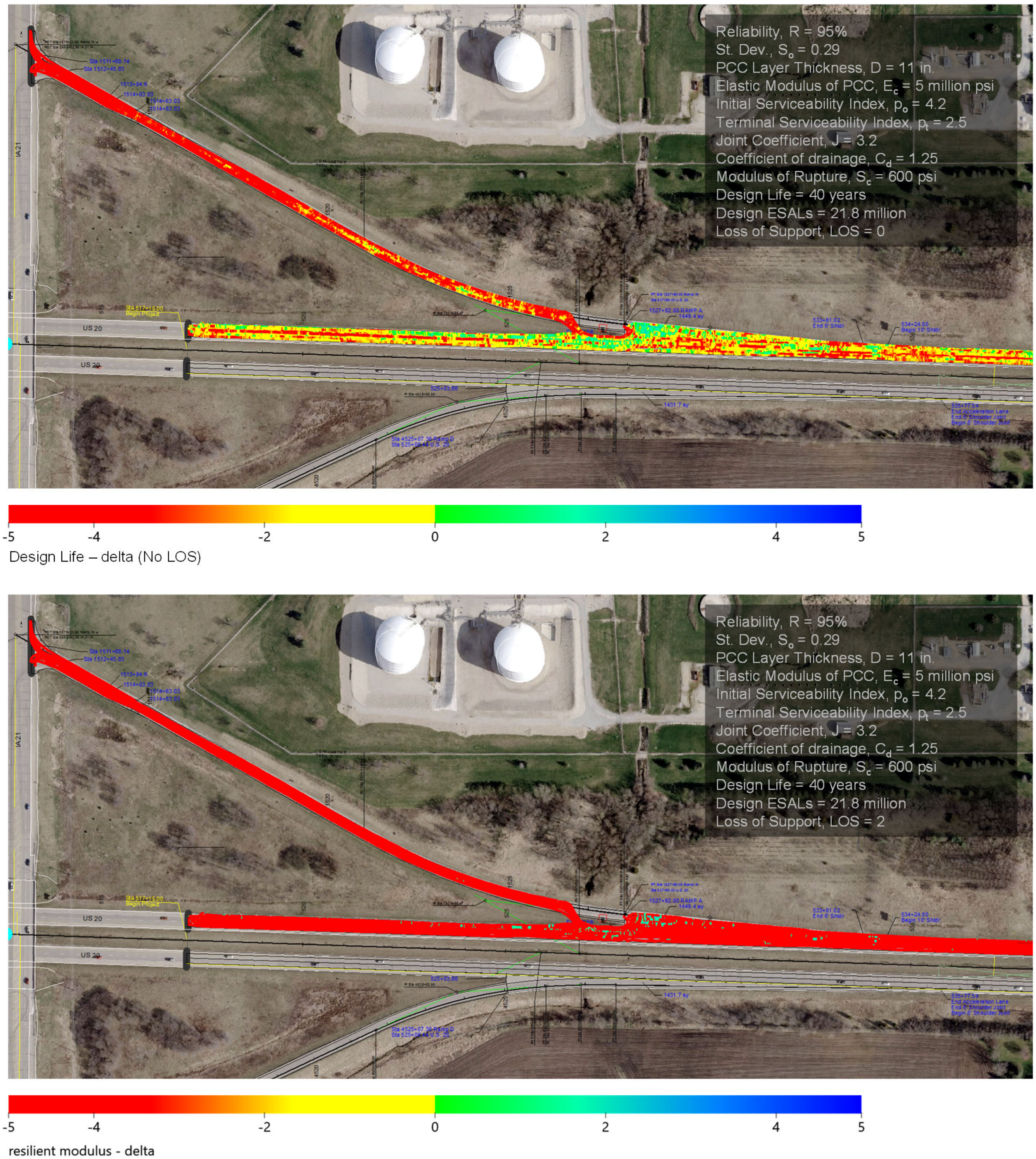


Figure 9. Predicted delta design life (assumed minus measured design life) using in situ k-value measurements from COMP-Score RT mapping with LOS (top) and without LOS – US20 Blackhawk County Project

Outreach Activities

The end goals of the field demonstrations conducted in this project were to provide hands-on experience to the Contractor and the Iowa DOT Engineers, garner feedback from stakeholders, and develop the associated modulus mapping specifications for future pavement foundation construction projects. Outreach activities were performed throughout the course of the project, and these included a nation-wide Survey organized by the Iowa DOT, technical working group meetings with stakeholders, and interactions with the FHWA.

National DOT Survey

The survey conducted as a part of this project included state and federal agencies with questions related to the current practice for pavement foundation inspection and interest/activity related to in situ modulus measurement. A total of 32 respondents from 31 transportation agencies responded to the survey (Figure 10). The questions and the responses are summarized in Appendix VII.

In review of the survey results, it is evident that although pavements in most states are meeting design life expectations, nearly two-thirds of respondents agree that pavements are being compromised because of foundation related issues. It is assumed that construction requirements are generally adequate to field control the quality of subgrade and base layers, and approximately three-fourths of states' construction specifications require the correction of problematic areas using a method other than compaction. The responded states have no direct acceptance requirements based upon pavement design engineering parameters. Respondents were asked what specific quality acceptance parameters are required and measured for pavement foundations and none of the responding states are currently measuring modulus of subgrade reaction or resilient modulus. However, almost all respondents thought it is important to field verify modulus values being used in pavement design.

In brief, there is agreement that pavement foundation issues contribute to compromised pavements, and almost all respondents agreed that it would be helpful to field verify modulus values used in pavement design, although currently no measurements are being performed. There was great interest in the Iowa DOT's future implementation efforts of the innovations demonstrated in this project.

Technical Working Group (TWG) and Project Meetings

Five project meetings were conducted between the Iowa DOT, FHWA, and Ingios between March 2019 and March 2020. The primary objectives of the project meetings were to identify potential project sites for demonstrations, results and findings from the ongoing field demonstration activities, demonstration of the e-Construction web interface, identification of the technical working group members to involve stakeholders from the construction industry, and identification of future implementation projects.

Two TWG meetings were conducted on April 15, 2020 and December 8, 2020, with stakeholders from the following organizations:

- Iowa DOT
- FHWA
- Association of General Contractor (AGC)
- Asphalt Paving Association of Iowa (APAI)
- Iowa Concrete Paving Association (ICPA), and
- Contractors (CJ Moyna, Manatts, Peterson, Streb)

During the technical working group meetings, the Iowa DOT and Ingios presented the broader project objectives, results from the demonstration projects, reviewed upcoming implementation pilot project opportunities, demonstrated the e-Construction web interface, and the special provisions developed for implementation. Feedback obtained from the TWG meetings were used to further refine the special provisions and develop project workflow to illustrate implementation of the technologies.

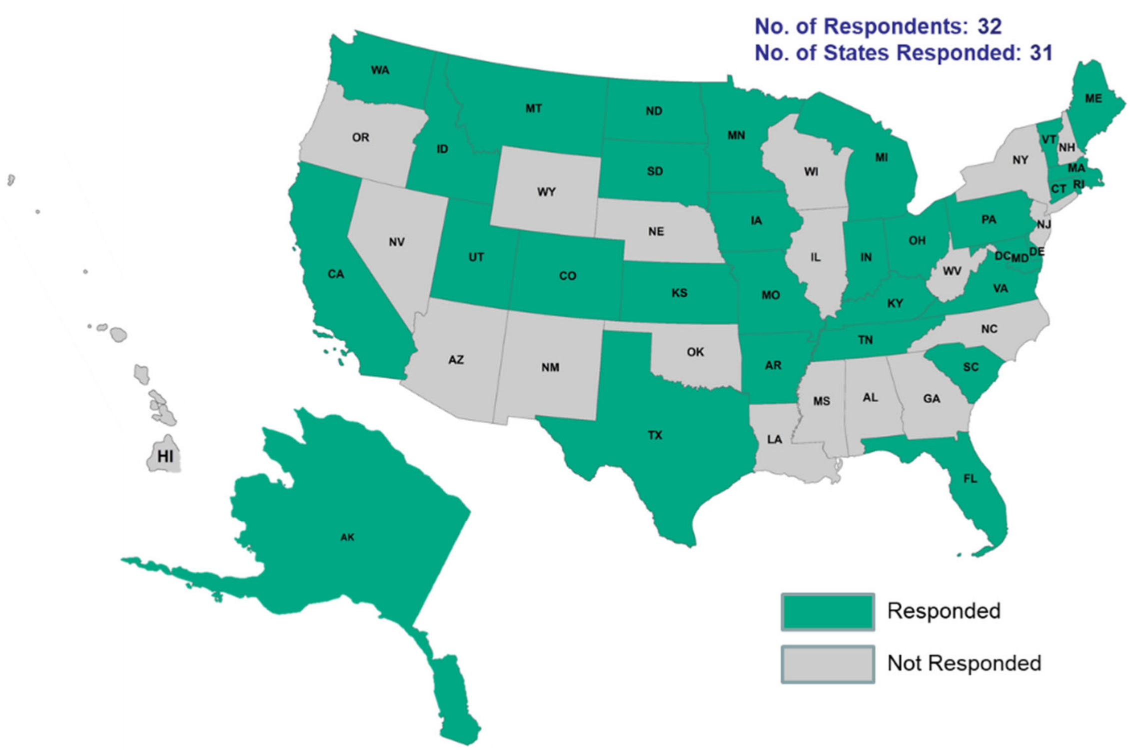


Figure 10. Map of survey responses by state.

Technology Transfer Activities

In addition to the project report, the following technology transfer activities were conducted and developed as part of the project:

- A technology brief highlighting the project objectives, deliverables, and the key findings.
- A Field Day was conducted on the US52 project in Dubuque County with several personnel from an earthwork contractor (CJ Moyna) and Iowa DOT, to provide on-site hands-on demonstration of the innovations.
- Training materials were developed for operators and engineers on how to use the modulus mapping technology and e-Compaction reporting web interface (see Appendix I).

DATA COLLECTION AND ANALYSIS

Performance measures consistent with the project goals were jointly established for this project by the Iowa DOT, Ingios, and FHWA to qualify, not to quantify, the effectiveness of the innovation to inform the AID Demonstration program in working toward best practices, programmatic performance measures, and future decision making guidelines.

Data was collected to determine the impact of using modulus based mapping and e-Compaction reporting on safety, cost, and quality, and demonstrate the ability to:

- Reduce life cycle costs through producing a high-quality project
- Reduce impacts to the traveling public and project abutters

This section discusses how the Iowa DOT and Ingios established baseline criteria, monitored and recorded data during the implementation of the innovation, and analyzed and assessed the results for each of the performance measures related to these focus areas.

SAFETY

The Iowa DOT and Ingios are always concerned with the safety of both the workers delivering the project and the users of our infrastructure during construction. Using the technology allows for direct verification of modulus in real-time and allows for corrective actions immediately. This can potentially reduce the roadway maintenance/repair work, thereby inherently improving the safety of both on site workers and the public. The scope of the project, however, does not allow for a thorough evaluation of the safety related impacts using the technology.

SCHEDULE

Improvement to pavement foundation layers during construction has typically been limited to moisture conditioning (drying) to address wet subgrade condition. Additional stabilization as alternatives (additional compaction, application of geogrid, cements stabilization, etc.) has typically not been included in projects partly due to not having actionable information to identify weak areas and incorporate this identification into the construction workflow process. By bringing a real-time solution to understanding where to improve pavement foundation layers, the Iowa DOT now has a means to identify and improve weak areas before the next step of construction is completed. This not only provides the Iowa DOT with an improvement in pavement foundation quality, it provides a real-time e-Construction solution that takes only minutes to document.

COST

Empirically, we have learned through prior Iowa Highway Research Board projects that enhancements to compaction quality and associated testing can initially increase projects cost. As discussed during the technical working group meetings, we assume this cost increase is on the order of 1% of the total bid price for the project. However, it is anticipated that the cost increase will be minimal over time as the new technology becomes part of the state of practice. To identify and study all costs associated with future projects using modulus verification mapping, the Iowa DOT plans to implement unit bid pricing for mapping and stabilization options. By tracking these cost elements, it will be possible to assess how these investments in pavement foundation quality track with pavement ride quality and maintenance/life-cycle costs.

QUALITY

As previously discussed, using traditional project delivery techniques the Iowa DOT would have implemented either moisture or moisture-density control on subgrade and embankment materials. The number of tests performed for material placed and the coverage it provides is virtually insignificant and the surrogate measurements do not provide a link to the design assumed values. This innovation allows direct measurement of the in situ modulus values as a direct verification of the design assumptions, provides 100% coverage of all pavement foundation layers as they are constructed, allows viewing results in real-time to perform corrective actions immediately, and creates a digital as-built records using e-Compaction reporting. Correcting areas that do not meet the minimum design requirements ensures that the unwanted maintenance costs in the future are minimized and the foundation layer provides adequate support during its service life.

USER COSTS

By delivering improved pavement foundation systems, the Iowa DOT expects pavement ride quality to be improved, have less maintenance activities, and extend pavement life. All these factors will positively impact the transportation public in Iowa by reducing vehicle operating costs, delay costs, and safety-related costs/crash costs.

USER SATISFACTION

This project addressed real-time construction of pavement foundation layers, which is the buried subterranean component of the pavement system that often requires years to demonstrate improvements for the road users. As part of the user satisfaction assessment for this project, we completed a national survey of state agencies with questions designed to garner feedback if there is interest in pavement foundation improvements and learning about the outcomes form this study. An overwhelming majority of responded expressed interest in this study and the desire to be engaged with the findings. See Appendix VII: NATIONAL DOT SURVEY FINDINGS AND RESULTS.

Project Outcomes and Lessons Learned

Through this project, the Iowa DOT and Ingios gained valuable insights about and from the modulus mapping results and e-Compaction reporting tools used.

Improving the quality of the foundations and ensuring the support conditions meet the minimum design assumptions allows for improved pavement performance, and thereby potentially less unnecessary maintenance costs. Improved performance and reduced maintenance on the roads allow for safe driving conditions on the roads for the public.

As an outcome of this project, the Iowa DOT has moved forward with two pilot projects for 2021 utilizing the implementation plan and construction special provisions developed during this project. The Iowa DOT anticipates that by implementing the new workflow processes and construction quality requirements, pavement performance will be significantly increased, resulting in not only lower life cycle ownership cost and less maintenance, but increased safety for the public.

Recommendations and Implementation

RECOMMENDATIONS

The Iowa DOT determined from the results of data analysis that modulus mapping results and e-Compaction reporting tools used can significantly improve pavement performance, and thereby reduce maintenance costs, and improve satisfaction to roadway users. The Iowa DOT proposes adopting the modulus mapping and e-Compaction reporting technologies into the DOT's standard operating procedures.

However, the following areas were identified that could be improved upon in future applications of this innovation:

- Provide an e-Compaction report page that shows thickness of material placed in each lift.
- Add an e-Compaction report page that specifically identifies areas of concern where further testing for modulus verification is warranted.

- Add an e-Compaction report page that identifies blob areas on a map with GPS coordinates for implementing corrective actions.

STATUS OF IMPLEMENTATION AND ADOPTION

Since the completion of *Increasing Pavement Performance through Pavement Foundation Design Modulus Verification and Construction Monitoring* project, the Iowa DOT has undertaken follow up activities to implement pavement design modulus verification and construction monitoring. As part of the AID project, a detailed implementation plan was developed which included the following elements:

1. A technical working group (TWG) comprised of FHWA, Iowa DOT, industry associations, and contractors was formed to review, provide feedback, and oversight of implementation activities.
2. Executive level presentations were given to Iowa DOT and industry leadership.
3. Detailed workflow processes were developed for both the current requirements and proposed requirements reflecting full implementation.
4. Special Provisions (SP) were developed for use on pilot projects in place of current specifications. The SP reflected extensive feedback obtained from the deployment activities conducted under the AID project.
5. Training programs were developed for agency and contractor personnel.
6. A national survey was conducted to identify potential technology partnerships.
7. Two pilot projects were identified for 2021:
    a. Boone County STP-017-2(23)—2C-08
    b. Blackhawk NHSX-20-6(72)—3H-07

Implementation of design modulus verification and construction monitoring included the following ongoing plan elements.

1. Continued engagement with the TWG.
2. Phased implementation from two pilot projects in 2021 to potentially full state-wide use in 2025. (The goal is to have project experience for each Resident Construction Engineer and District Office during the implementation period.)

2021	• 2 pilot projects bid with SPs • Modulus mapping of selected grading projects to support pavement design • Agency and industry training
2022	• 4-5 pilot projects
2023	• ~10 pilot projects
2024	• ~ 20 pilot projects
2025	• Full deployment as an agency standard

3. Development of a parallel program to support local jurisdictions.
4. Adopt standard specifications and new agency workflow processes in 2025.

The detailed implementation plan and timeline is included in Appendix VI.