CIAMTIS

U.S. DOT Region 3 University Transportation Center

CIAMTIS Lehigh Research Experience for Undergraduates (REU) Program

October 29, 2021

Prepared by:
R. Sause, Lehigh University; C. Kusko, Lehigh University

r3utc.psu.edu

PennState College of Engineering | LARSON TRANSPORTATION INSTITUTE

Technical Report Documentation Page

1. Report No. CIAM-COR-R31	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle CIAMTIS Lehigh Research Experience for Undergraduates (REU) Program		**5. Report Date** October 30, 2021
		6. Performing Organization Code
7. Author(s) Richard Sause, Chad S. Kusko		**8. Performing Organization Report No.**
9. Performing Organization Name and Address Lehigh University ATLSS Engineering Research Center 117 ATLSS Drive Bethlehem, PA 18015		**10. Work Unit No. (TRAIS)**
		11. Contract or Grant No. 69A3551847103
12. Sponsoring Agency Name and Address U.S. Department of Transportation Research and Innovative Technology Administration 3rd Fl, East Bldg E33-461 1200 New Jersey Ave, SE Washington, DC 20590		**13. Type of Report and Period Covered** Final Report 3/1/2021 – 9/30/2021
		14. Sponsoring Agency Code

15. Supplementary Notes

Work funded through The Pennsylvania State University through the University Transportation Center Grant Agreement, Grant No. 69A3551847103.

16. Abstract

Lehigh University, through its Institute for Cyber Physical Infrastructure and Energy (I-CPIE) and its Advanced Technology for Large Structural Systems (ATLSS) Engineering Research Center, in conjunction with the Pennsylvania Infrastructure Technology Alliance (PITA) program, conducted a virtual 10-week CIAMTIS Lehigh Research Experience for Undergraduates (REU) program. The program, which ran from June 2, 2021 through August 6, 2021, featured Lehigh University students who participated in a virtual program that exposed the students to a well-rounded experience, including both research-focused and professional development-focused activities. The program's activities included professional skills development workshops in addition to the assignment of students to an active CIAMTIS research project at ATLSS or a technical project related to the mission of CIAMTIS under the direction of the project Principal Investigator and graduate student mentor to help them navigate through the research project experience. The program culminated with a final report, presentation, and poster on their research findings.

17. Key Words Research Experience for Undergraduates, CIAMTIS, ATLSS Engineering Research Center		**18. Distribution Statement** No restrictions. This document is available from the National Technical Information Service, Springfield, VA 22161	
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 9	**22. Price**

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

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

Introduction

BACKGROUND

Lehigh University, through its Institute for Cyber Physical Infrastructure and Energy (I-CPIE) and its Advanced Technology for Large Structural Systems (ATLSS) Engineering Research Center, in conjunction with Lehigh University's STEM Summer Institutes (STEM-SI) program, conducted a 10-week CIAMTIS Lehigh Research Experience for Undergraduates (REU) program. The program ran from June 2, 2021 through August 6, 2021. Lehigh University undergraduate students participated in the research-centric program, which exposed the students to a well-rounded professional development experience. Students were assigned to an active CIAMTIS research project at ATLSS or a research project that fit within the mission of CIAMTIS under the direction of the project Principal Investigator and graduate student mentor to help them navigate through the research project experience. Additionally, program activities included professional skills development workshops and trainings. The program culminated with a final report, presentation, and poster on their research findings.

OBJECTIVES

The objective of the REU program is to provide the students with a well-rounded professional development experience, featuring research as part of an active CIAMTIS research project at Lehigh University or a research project that fits withn the mission of CIAMTIS, and also including professional skills development workshops and seminars. This program exposed the students to research areas important to CIAMTIS while providing the students with research and professional development training that will prepare the students for future professional endeavors.

DATA AND DATA STRUCTURES

The participating students developed final reports, presentations, and posters. Copies of the final reports and posters are included within Appendix A of this final report.

CHAPTER 2

Methodology

INTRODUCTION

The REU program was conducted under the following criteria:

1. CIAMTIS Lehigh project principal investigators identified candidate students to participate in the Summer 2021 CIAMTIS Lehigh REU program. Additionally, an announcement regarding the STEM-SI program opportunities was distributed to Lehigh University undergraduate Civil and Environmental Engineering students for program consideration.

2. Recommendations and resumes were reviewed and interviews conducted, as necessary, in order to identify a candidate student for each active CIAMTIS Lehigh research project.

3. REU program dates were finalized as June 2, 2021 – August 6, 2021.

4. Students identified for the program were notified of their selection.

5. Principal Investigators and graduate student mentors were finalized for each project.

7. Program workshops and seminars were identified and scheduled.

8. Operation of the CIAMTIS Lehigh REU program, including workshops and project research, took place under the direction of the project Principal Investigator and project mentors.

9. Program participants completed final reports, posters, and formal presentations at the conclusion of the program.

CHAPTER 3

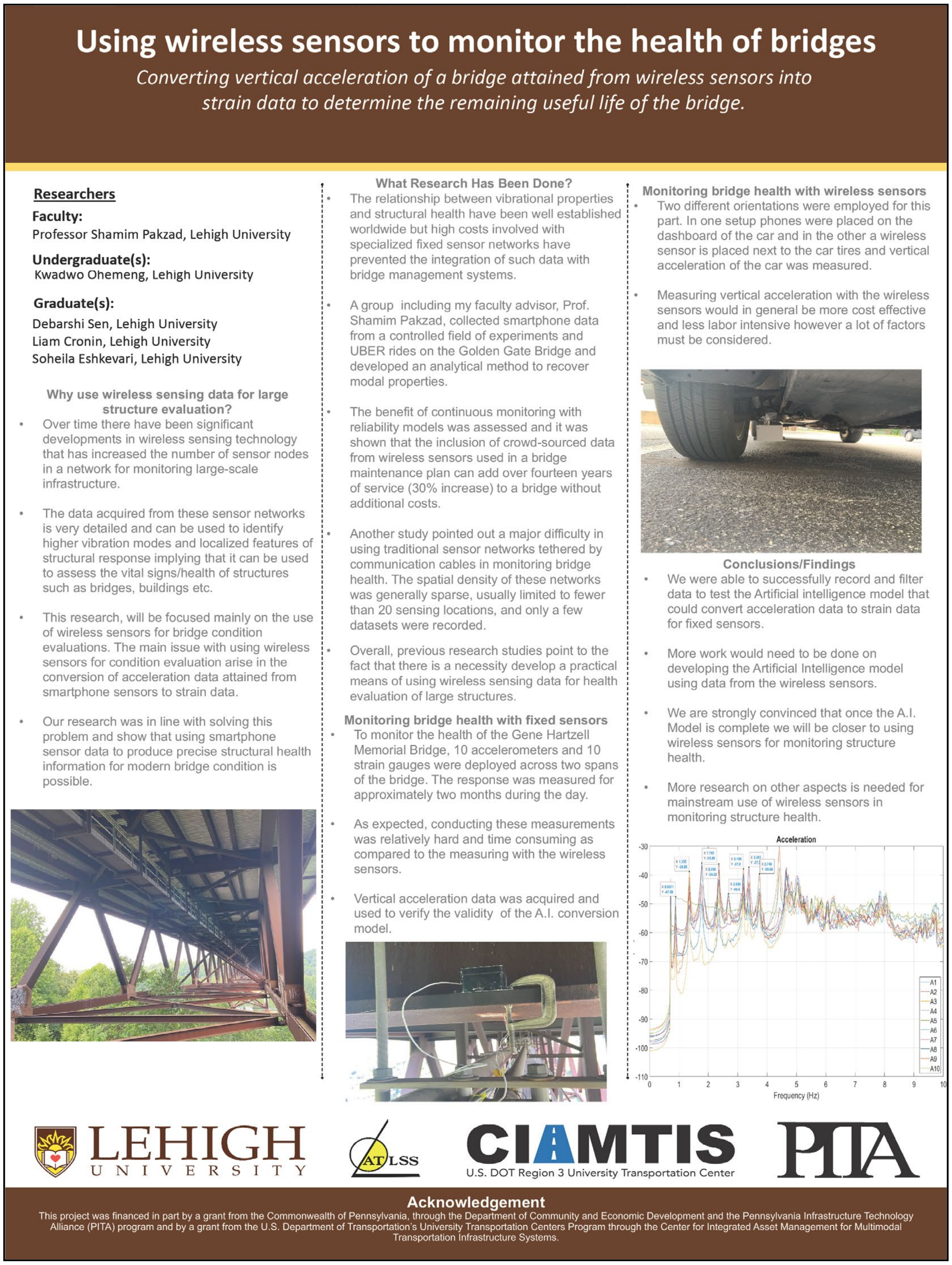
Findings

The project matrix, along with particpating students, for the CIAMTIS Lehigh REU program is presented in Table 1. Participating students are shown in Figure 1 in front of the ATLSS Engineering Research Center at Lehigh University. Each student conducted research on a project under the direction of a PI and project mentor. The results of this research were summarized in final project reports, which accompany this report in Appendix A, along with final posters, which are shown in Figures 2-4. Each student made a final program presentation to the project PIs prior to the conclusion of the program.

Table 1. Project, student, university, PI and mentor matrix for the 2021 CIAMTIS Lehigh REU program.

CIAMTIS Project Title	REU Student	University	PI	Mentor
Using Wireless Sensors to Monitor the Health of Bridges	Kwadwo Ohemeng	Lehigh University	Shamim Pakzad / Martin Takac	
Investigation of the Benefit of Using a Novel Corrosion Resistant Steel in New and Existing Steel Bridges in Pennsylvania	Alexis Javier	Lehigh University	Dan Frangopol	Xu Han
Direct Tensile Testing of Ultra High Performance Concrete	John Wagner	Lehigh University	Clay Naito	Shuoyu Wang

Figure 1. CIAMTIS Lehigh REU students. From left to right: Kwadwo Ohemeng, John Wagner, and Alexis Javier.



Using wireless sensors to monitor the health of bridges

Converting vertical acceleration of a bridge attained from wireless sensors into strain data to determine the remaining useful life of the bridge.

Researchers

Faculty:
Professor Shamim Pakzad, Lehigh University

Undergraduate(s):
Kwadwo Ohemeng, Lehigh University

Graduate(s):
Debarshi Sen, Lehigh University
Liam Cronin, Lehigh University
Soheila Eshkevari, Lehigh University

Why use wireless sensing data for large structure evaluation?

- Over time there have been significant developments in wireless sensing technology that has increased the number of sensor nodes in a network for monitoring large-scale infrastructure.
- The data acquired from these sensor networks is very detailed and can be used to identify higher vibration modes and localized features of structural response implying that it can be used to assess the vital signs/health of structures such as bridges, buildings etc.
- This research, will be focused mainly on the use of wireless sensors for bridge condition evaluations. The main issue with using wireless sensors for condition evaluation arise in the conversion of acceleration data attained from smartphone sensors to strain data.
- Our research was in line with solving this problem and show that using smartphone sensor data to produce precise structural health information for modern bridge condition is possible.

What Research Has Been Done?

- The relationship between vibrational properties and structural health have been well established worldwide but high costs involved with specialized fixed sensor networks have prevented the integration of such data with bridge management systems.
- A group including my faculty advisor, Prof. Shamim Pakzad, collected smartphone data from a controlled field of experiments and UBER rides on the Golden Gate Bridge and developed an analytical method to recover modal properties.
- The benefit of continuous monitoring with reliability models was assessed and it was shown that the inclusion of crowd-sourced data from wireless sensors used in a bridge maintenance plan can add over fourteen years of service (30% increase) to a bridge without additional costs.
- Another study pointed out a major difficulty in using traditional sensor networks tethered by communication cables in monitoring bridge health. The spatial density of these networks was generally sparse, usually limited to fewer than 20 sensing locations, and only a few datasets were recorded.
- Overall, previous research studies point to the fact that there is a necessity develop a practical means of using wireless sensing data for health evaluation of large structures.

Monitoring bridge health with fixed sensors

- To monitor the health of the Gene Hartzell Memorial Bridge, 10 accelerometers and 10 strain gauges were deployed across two spans of the bridge. The response was measured for approximately two months during the day.
- As expected, conducting these measurements was relatively hard and time consuming as compared to the measuring with the wireless sensors.
- Vertical acceleration data was acquired and used to verify the validity of the A.I. conversion model.

Monitoring bridge health with wireless sensors

- Two different orientations were employed for this part. In one setup phones were placed on the dashboard of the car and in the other a wireless sensor is placed next to the car tires and vertical acceleration of the car was measured.
- Measuring vertical acceleration with the wireless sensors would in general be more cost effective and less labor intensive however a lot of factors must be considered.

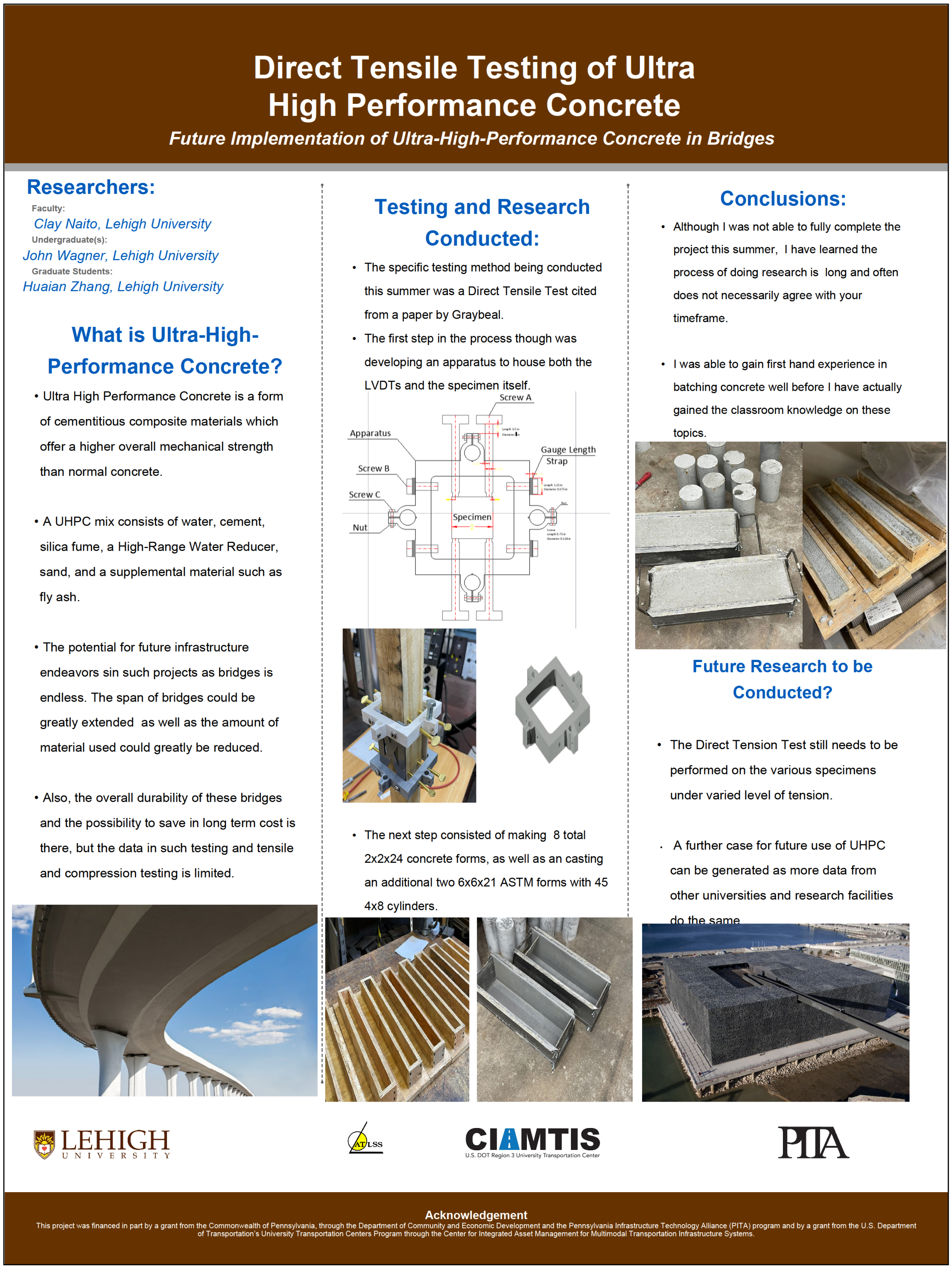
Conclusions/Findings

- We were able to successfully record and filter data to test the Artificial intelligence model that could convert acceleration data to strain data for fixed sensors.
- More work would need to be done on developing the Artificial Intelligence model using data from the wireless sensors.
- We are strongly convinced that once the A.I. Model is complete we will be closer to using wireless sensors for monitoring structure health.
- More research on other aspects is needed for mainstream use of wireless sensors in monitoring structure health.

Acknowledgement

This project was financed in part by a grant from the Commonwealth of Pennsylvania, through the Department of Community and Economic Development and the Pennsylvania Infrastructure Technology Alliance (PITA) program and by a grant from the U.S. Department of Transportation's University Transportation Centers Program through the Center for Integrated Asset Management for Multimodal Transportation Infrastructure Systems.

Figure 2. Project poster for CIAMTIS project titled *Using Wireless Sensors to Monitor the Health of Bridges.*



Direct Tensile Testing of Ultra High Performance Concrete

Future Implementation of Ultra-High-Performance Concrete in Bridges

Researchers:

Faculty:
Clay Naito, Lehigh University
Undergraduate(s):
John Wagner, Lehigh University
Graduate Students:
Huaian Zhang, Lehigh University

What is Ultra-High-Performance Concrete?

- Ultra High Performance Concrete is a form of cementitious composite materials which offer a higher overall mechanical strength than normal concrete.
- A UHPC mix consists of water, cement, silica fume, a High-Range Water Reducer, sand, and a supplemental material such as fly ash.
- The potential for future infrastructure endeavors sin such projects as bridges is endless. The span of bridges could be greatly extended as well as the amount of material used could greatly be reduced.
- Also, the overall durability of these bridges and the possibility to save in long term cost is there, but the data in such testing and tensile and compression testing is limited.

Testing and Research Conducted:

- The specific testing method being conducted this summer was a Direct Tensile Test cited from a paper by Graybeal.
- The first step in the process though was developing an apparatus to house both the LVDTs and the specimen itself.

- The next step consisted of making 8 total 2x2x24 concrete forms, as well as an casting an additional two 6x6x21 ASTM forms with 45 4x8 cylinders.

Conclusions:

- Although I was not able to fully complete the project this summer, I have learned the process of doing research is long and often does not necessarily agree with your timeframe.
- I was able to gain first hand experience in batching concrete well before I have actually gained the classroom knowledge on these topics.

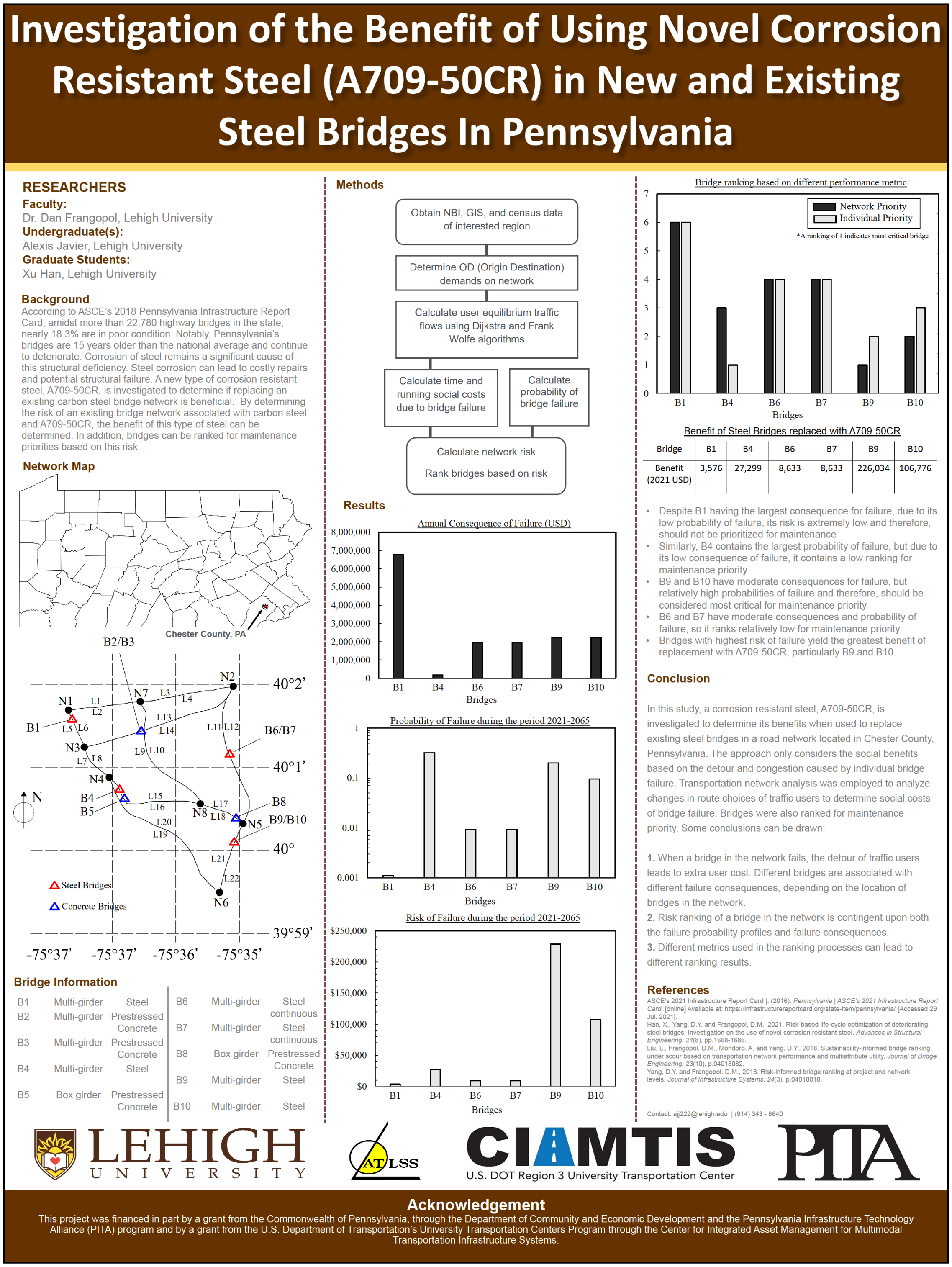
Future Research to be Conducted?

- The Direct Tension Test still needs to be performed on the various specimens under varied level of tension.
- A further case for future use of UHPC can be generated as more data from other universities and research facilities do the same.

Acknowledgement

This project was financed in part by a grant from the Commonwealth of Pennsylvania, through the Department of Community and Economic Development and the Pennsylvania Infrastructure Technology Alliance (PITA) program and by a grant from the U.S. Department of Transportation's University Transportation Centers Program through the Center for Integrated Asset Management for Multimodal Transportation Infrastructure Systems.

Figure 3. Project poster for CIAMTIS project titled *Direct Tensile Testing of Ultra High Performance Concrete*.



Investigation of the Benefit of Using Novel Corrosion Resistant Steel (A709-50CR) in New and Existing Steel Bridges In Pennsylvania

RESEARCHERS

Faculty:
Dr. Dan Frangopol, Lehigh University
Undergraduate(s):
Alexis Javier, Lehigh University
Graduate Students:
Xu Han, Lehigh University

Background

According to ASCE's 2018 Pennsylvania Infrastructure Report Card, amidst more than 22,780 highway bridges in the state, nearly 18.3% are in poor condition. Notably, Pennsylvania's bridges are 15 years older than the national average and continue to deteriorate. Corrosion of steel remains a significant cause of this structural deficiency. Steel corrosion can lead to costly repairs and potential structural failure. A new type of corrosion resistant steel, A709-50CR, is investigated to determine if replacing an existing carbon steel bridge network is beneficial. By determining the risk of an existing bridge network associated with carbon steel and A709-50CR, the benefit of this type of steel can be determined. In addition, bridges can be ranked for maintenance priorities based on this risk.

Network Map

Bridge Information

B1	Multi-girder	Steel
B2	Multi-girder	Prestressed Concrete
B3	Multi-girder	Prestressed Concrete
B4	Multi-girder	Steel
B5	Box girder	Prestressed Concrete
B6	Multi-girder	Steel continuous
B7	Multi-girder	Steel continuous
B8	Box girder	Prestressed Concrete
B9	Multi-girder	Steel
B10	Multi-girder	Steel

Methods

Obtain NBI, GIS, and census data of interested region

Determine OD (Origin Destination) demands on network

Calculate user equilibrium traffic flows using Dijkstra and Frank Wolfe algorithms

Calculate time and running social costs due to bridge failure

Calculate probability of bridge failure

Calculate network risk

Rank bridges based on risk

Results

Annual Consequence of Failure (USD)

Probability of Failure during the period 2021-2065

Risk of Failure during the period 2021-2065

Bridge ranking based on different performance metric

Benefit of Steel Bridges replaced with A709-50CR

Bridge	B1	B4	B6	B7	B9	B10
Benefit (2021 USD)	3,576	27,299	8,633	8,633	226,034	106,776

- Despite B1 having the largest consequence for failure, due to its low probability of failure, its risk is extremely low and therefore, should not be prioritized for maintenance
- Similarly, B4 contains the largest probability of failure, but due to its low consequence of failure, it contains a low ranking for maintenance priority
- B9 and B10 have moderate consequences for failure, but relatively high probabilities of failure and therefore, should be considered most critical for maintenance priority
- B6 and B7 have moderate consequences and probability of failure, so it ranks relatively low for maintenance priority
- Bridges with highest risk of failure yield the greatest benefit of replacement with A709-50CR, particularly B9 and B10.

Conclusion

In this study, a corrosion resistant steel, A709-50CR, is investigated to determine its benefits when used to replace existing steel bridges in a road network located in Chester County, Pennsylvania. The approach only considers the social benefits based on the detour and congestion caused by individual bridge failure. Transportation network analysis was employed to analyze changes in route choices of traffic users to determine social costs of bridge failure. Bridges were also ranked for maintenance priority. Some conclusions can be drawn:

1. When a bridge in the network fails, the detour of traffic users leads to extra user cost. Different bridges are associated with different failure consequences, depending on the location of bridges in the network.
2. Risk ranking of a bridge in the network is contingent upon both the failure probability profiles and failure consequences.
3. Different metrics used in the ranking processes can lead to different ranking results.

References

ASCE's 2021 Infrastructure Report Card |. (2016). *Pennsylvania | ASCE's 2021 Infrastructure Report Card*. [online] Available at: https://infrastructurereportcard.org/state-item/pennsylvania/ [Accessed 29 Jul. 2021].
Han, X., Yang, D.Y. and Frangopol, D.M., 2021. Risk-based life-cycle optimization of deteriorating steel bridges: Investigation on the use of novel corrosion resistant steel. *Advances in Structural Engineering*, *24*(8), pp.1668-1686.
Liu, L., Frangopol, D.M., Mondoro, A. and Yang, D.Y., 2018. Sustainability-informed bridge ranking under scour based on transportation network performance and multiattribute utility. *Journal of Bridge Engineering*, *23*(10), p.04018082.
Yang, D.Y. and Frangopol, D.M., 2018. Risk-informed bridge ranking at project and network levels. *Journal of Infrastructure Systems*, *24*(3), p.04018018.

Contact: ajj222@lehigh.edu | (914) 343 - 8640

Acknowledgement
This project was financed in part by a grant from the Commonwealth of Pennsylvania, through the Department of Community and Economic Development and the Pennsylvania Infrastructure Technology Alliance (PITA) program and by a grant from the U.S. Department of Transportation's University Transportation Centers Program through the Center for Integrated Asset Management for Multimodal Transportation Infrastructure Systems.

Figure 4. Project poster for CIAMTIS project titled *Investigation of the Benefit of Using Novel Corrosion Resistant Steel (A709-50CR) in New and Existing Steel Bridges in Pennsylvania*.

The REU Program

Beyond the research project, the students engaged in various professional development activities throughout the duration of the 10-week program, as outlined below:

- Orientation and Training sessions:
    - Program orientation integrated with Lehigh University's STEM-SI program and focused on :
        - Laboratory Safety, by Randy Shebby, Assistant Director, Department of Environmental Health and Safety, Lehigh University
        - Research Ethics, by Neal Simon, Professor, Biological Sciences, and Vassie Ware, Professor, Biological Sciences, Lehigh University
    - Technical report writing presentation
    - Online tutorial on Library Resources prepared by Philip Hewitt, Senior Engineering College Librarian
- Professional development sessions:
    - *Career Exploration and Decision Making* by Andrea Reger, Associate Director, Career Services, Lehigh University
    - *Resume & Cover Letter Lab* by Andrea Reger, Associate Director, Career Services, Lehigh University
    - *How to Conduct an Effective Internship or Job Search & Building Your Professional Network* by Ali Erk, Associate Director, Graduate Student Career Development, Lehigh University
    - *Successful Interviewing* by Ali Erk, Associate Director, Graduate Student Career Development, Lehigh University
    - *Graduate School Admissions and Graduate School Preparation and Expectations* by Lehigh University faculty and gradudate school alumni
- Weekly community development research seminars by faculty and industry representatives
- Weekly morning cafe group discussions
- Research activities:
    - Students worked on their respective CIAMTIS-focused projects
- Final Presentations:
    - Students made 15-minute final presentations with accompanying question and answer session.

CHAPTER 4

Recommendations

Future REU Program

Participating REU students were provided with a well-rounded professional development experience that focused on conducting research as part of active CIAMTIS research projects at Lehigh University under the direction of project PIs and mentors. Three participating REU students also engaged in training and orientation sessions, professional development sessions, seminars, and research group activities focused on enhancing the students' overall professional skills and exposure.

Lehigh's CIAMTIS administration plans on continuing the REU program in the Summer of 2022.

Appendix A

CIAMTIS

U.S. DOT Region 3 University Transportation Center

Using wireless sensors to monitor the health of bridges

August 5th,2021

Prepared by:

K.Ohemeng, Lehigh University

Technical Report Documentation Page

1. Report No. [UTC assigned]	**2. Government Accession No.**	**3. Recipient's Catalog No.**

4. Title and Subtitle Using wireless sensors to monitor the vital signs of bridges	**5. Report Date** [August 5 2021]
	6. Performing Organization Code
7. Author(s) [Kwadwo K. Ohemeng]	**8. Performing Organization Report No.**
9. Performing Organization Name and Address [Name and address of performing institution]	**10. Work Unit No. (TRAIS)**
	11. Contract or Grant No. [Enter contract number here]
12. Sponsoring Agency Name and Address U.S. Department of Transportation Research and Innovative Technology Administration 3rd Fl, East Bldg E33-461 1200 New Jersey Ave, SE Washington, DC 20590	**13. Type of Report and Period Covered** Draft Final Report xx/xx/20xx – xx/xx/20xx
	14. Sponsoring Agency Code
15. Supplementary Notes [Enter sponsor contact's Name, Email, Phone]	
16. Abstract [Enter abstract here]	
17. Key Words [Enter key words here]	**18. Distribution Statement** No restrictions. This document is available from the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** XXX	**22. Price**

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

Table of Content

CHAPTER 1

Introduction

BACKGROUND

Large structures such as bridges need to be checked over certain time frames due to the large weight loads and conditions they withstand. Over time there has been a great increase in the development of wireless sensor technology and thus an increase in the number of sensor nodes in a network for monitoring large structure can be increased by large orders of magnitude. The data gathered from this sensor technology is very detailed and can be used to used to identify higher vibration modes and localized features of structural response implying that it can be used to check the vital signs of structures such as briges, buildings etc. In this research we will focus mainly on the wireless sensor data used for modern bridge condition evaluations.

OBJECTIVES

The main objective of this research is to use wireless sensors in crowdsensing to produce precise structural health information under real-world conditions for modern bridge condition evaluations. It will be shown that data collected from smartphones in moving vehicles under real-world conditions can be used to identify structural modal properties of a bridge, information which is vital to bridge condition assessments and damage detection frameworks in them. This research, will be focused mainly on the use of wireless sensors for bridge condition evaluations. The main issue with using wireless sensors for condition evaluation arise in the conversion of acceleration data attained from smartphone sensors to strain data.

DATA AND DATA STRUCTURES

This research will be conducted in two main parts. For the first part we deploy fixed sensors on our bridge that have been traditionally used for modern bridge condition evaluations. Deploying these fixed sensors, we will gather information relevant to modern bridge condition evaluations. Then in the second part of the research we will use mobile phone sensors to repeat the same methodology and gather similar information on the bridge.

Using Fixed Sensors

Deploying the fixed sensors on the bridges is rather time and energy consuming, which immediately shows the necessity for an easier method to conduct modern bridge condition evaluations. After deploying the sensors on the bridge relevant data for modern bridge condition evaluations is collected.

Using Mobile Phone sensors

Using mobile phone sensors to collect data on the other hand is a lot easier to achieve due to the large number of mobile phone users that cross bridges. After driving over the bridge a number of times to collect relevant data, the data is also used for modern bridge condition evaluations.

CHAPTER 2

Methodology

INTRODUCTION

This section of the report describes the methodology used to conduct the research. In conducting this research there will be two main parts. In the first part we will install fixed accelerometers and strain gauges along the Gene-Hartzell Memorial bridge and use the data logger to measure the vibrations of the bridge. For the second part of it, we will now be using smart phones and wirless sensors in vehicles to measure these vertical acceleration when driving over the bridge.

Fixed Sensors

To monitor the health of the Gene Hartzell Memorial Bridge, 10 accelerometers and 10 strain gauges were deployed across two spans of the bridge. The response was measured for approximately two months during the day. As expected, conducting these measurements was relatively hard and time consuming as compared to the measuring with the wireless sensors. Vertical acceleration data was acquired and used to verify the validity of the A.I. conversion model.

Smart Phones

Two different orientations were employed for this part. In one setup phones were placed on the dashboard of the car and in the other a wireless sensor is placed next to the car tires and vertical acceleration of the car was measured. Measuring vertical acceleration with the wireless sensors would in general be more cost effective and less labor intensive however a lot of factors must be considered.

Data Processing

Vertical Acceleration and strain data from the Gene-Hartzell bridge was filtered, detrending after being recorded. This data after going through the cleaning process was to be used to verify the validity of the Artificial intelligence model that could deduce the relationship between vertical acceleration of the bridge and the amount of strain it is experiencing.

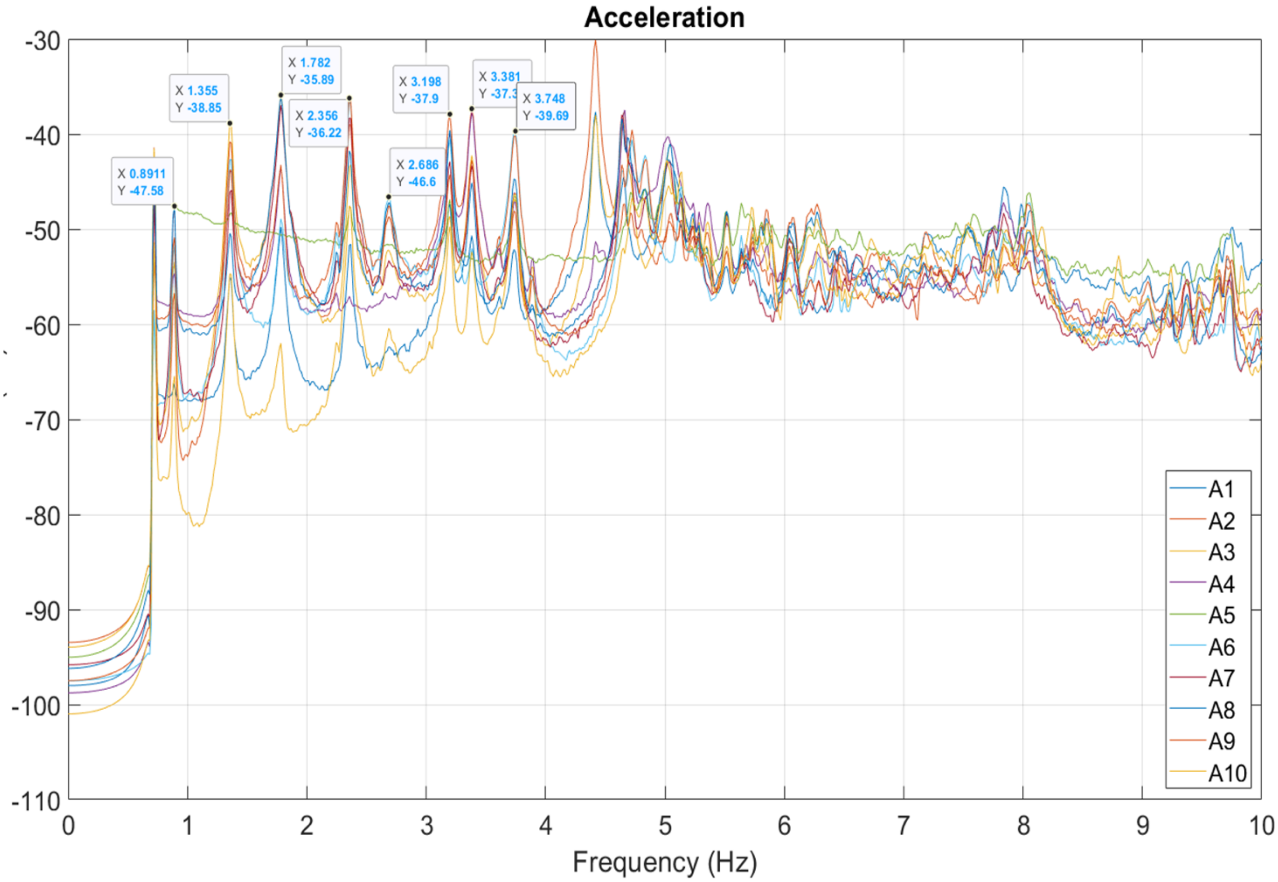


Figure 1. Vertical acceleration of Gene-Hartzell bridge over a 6-7 hour period

CHAPTER 3

Findings/Future Work

Over the two month period of research, this section describes what was achieved and the future of the research.

Accomplisments

We were able to successfully record and filter to test the Artificial intelligence model that could convert acceleration data to strain data for fixed sensors. Additionally, we were able to figure a variety of dynamic characteristics of the Gene-Hartzell bridge such as the frequency of its vibration, modal shapes, damping etc.

Future Work

Moving forward, more work would need to be done on developing the Artificial Intelligence model using data from the wireless sensors. Additionally, more research on other aspects is needed for mainstream use of wireless sensors in monitoring structure health.

CIAMTIS

U.S. DOT Region 3 University Transportation Center

Direct Tensile Testing of Ultra High Performance Concrete

Future Implementation of Ultra High Performance Concrete in Bridges

August 6th, 2021

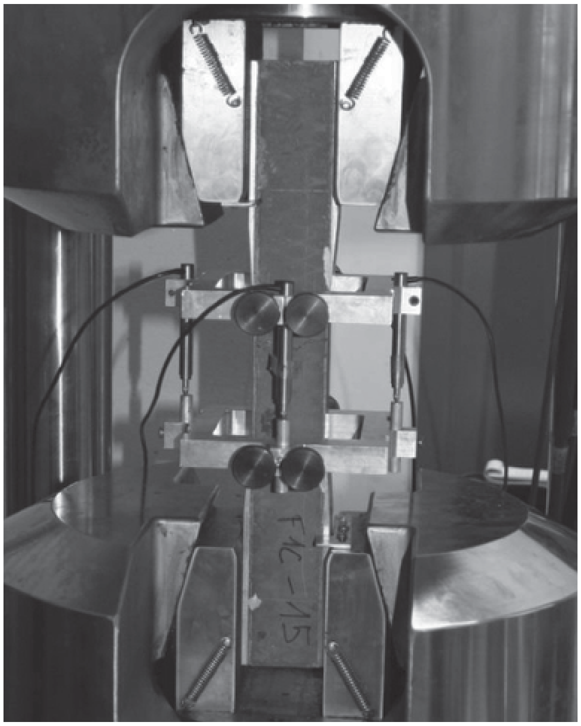
Prepared by:
J Wagner; Lehigh University
jew323@lehigh.edu

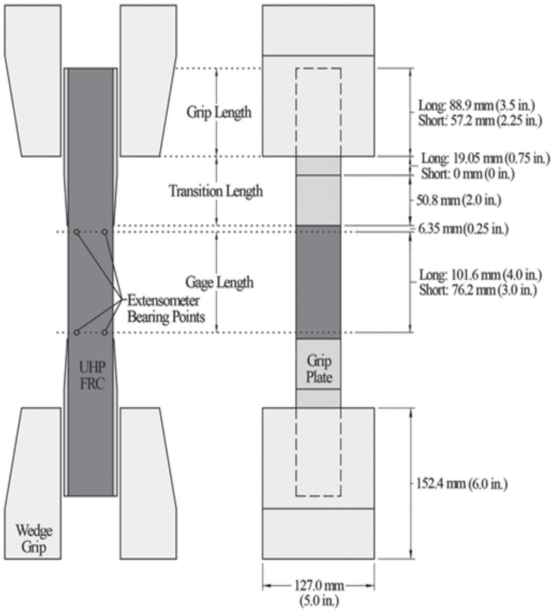
Introduction

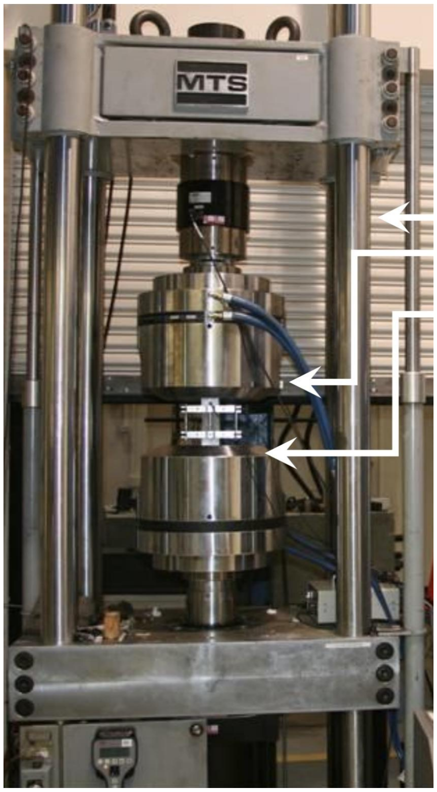
My project this summer is titled Direct Tensile Testing of Ultra High Performance Concrete with a focus a possible implementation in bridges within the near future . As a point of reference lets look at the infrastructure within the United States. From the 2021 ASCE report card, the United States receives a C- in regards to that of its overall infrastructure. This can be attributed for a long list of reasons, but for the most part it is a lack of funding and age at play. If we look even further into a specific area bridges, the United States receives a C. “With more than 600,000 plus bridges within the US, 42% are 50 years old and older. A recent estimate for the nation’s backlog of bridge repair needs is $125 billion. We need to increase spending on bridge rehabilitation from $14.4 billion annually to $22.7 billion annually, or by 58%, if we are to improve the condition(ASCE).” While several states have made strides to fix their bridges, Pennsylvania remains at a D+ with the state of their bridges. Pennsylvania bridges are at least 10 years older than that of the national average and much investment is required to strengthen this key area.hanks to funding by the Pennsylvania Infrastructure Technology Alliance and a grant from the United States Department of Transportation this summer I was able to start a project that will eventually be able to fix the problems of cost and durability in the United States’ infrastructure. Using some of the available funding, I was able to touch of the surface of Ultra High Performance Concrete. Before I dive into the research performed this summer, we first must define what is UHPC. Ultra-high-performance concrete (UHPC) is a new class of concrete that relies on a highly refined microstructure and fiber reinforcement to achieve superior performance characteristics, including high compressive strength, post-cracking tensile strength and ductility, and exceptional long-term durability in aggressive environments. Despite these desirable performance characteristics, applications of UHPC in the United States have been primarily limited to joints between precast bridge deck panels and a small number of demonstration projects in states such as Iowa and New York. A shortage of national design guidelines has resulted in reluctance by designers and owners to accept and utilize this material in more widespread applications, such as precast pretensioned elements for bridge and building projects. A UHPC mix consists of water, cement, silica fume, a High-Range Water Reducer, sand, and a supplemental material such as fly ash. Due to this lack of overall testing data related to both compressive strength and tensile strength of UHPC the lack of specifications for the girders as stated before make it hard to justify present use.The potential for future infrastructure endeavors sin such projects as bridges is endless. The span of bridges could be greatly extended as well as the amount of material used could greatly be reduced. Also, the overall durability of these bridges and the possibility to save in long term cost is there. In a paper by Graybeal, a tensile test was proposed to design the flexural strength and shear strength of the girder.

Methodology

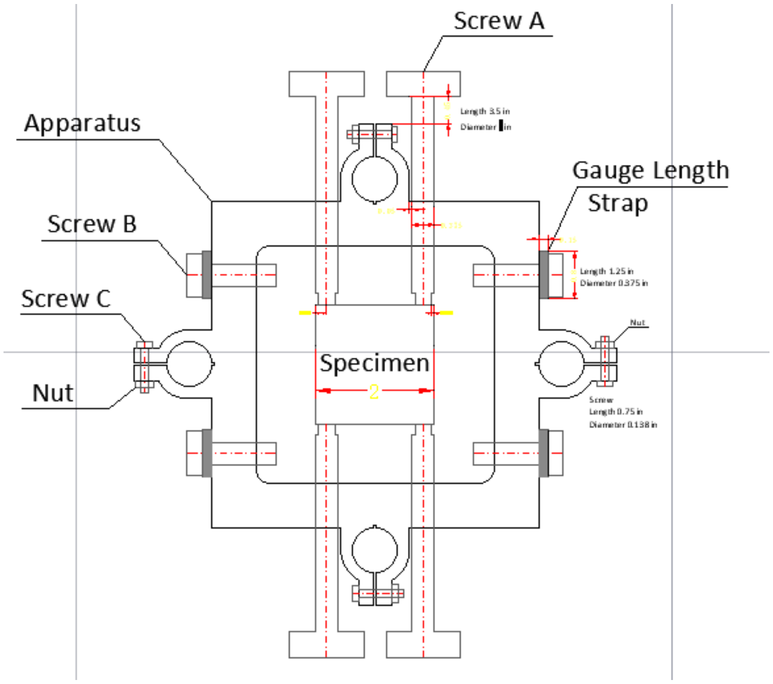
In 2013, a paper by Benjamin Graybeal and colleagues began to define the specifications for such testing methods for testing the tensile strength of UHPC. This data would be collected through a Direct Tensile testing.The test program included both a development phase and an execution phase. In the development phase, a series of physical and analytical tests were completed to assess the impact of a variety of grip-plate configurations on the performance of a specimen during a test. The analytical modeling was completed through the use of finite element modeling software. The UHPFRC and aluminum plates were modeled under the assumptions of linear elastic behavior with perfect bond between the UHPFRC and the plates, and the moduli of elasticity were assumed to be 55 and 70 GPa (7980 and 10,150 ksi), respectively. A variety of aluminum grip-plate thicknesses and transition geometries were considered to minimize the magnitude of the stress disturbance within the prismatic portion of the UHPFRC test specimen. The specimens created themselves were slated to be put under stress from 0 to failure with the post cracking tensile responses being measured through localization. The first part of this research assignment would first involve the development of both the apparatuses to house the specimens and then the casting of specimens.

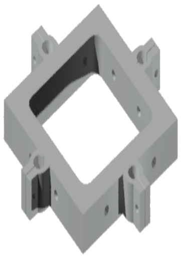



Grip Length
Long: 88.9 mm (3.5 in.)
Short: 57.2 mm (2.25 in.)
Long: 19.05 mm (0.75 in.)
Short: 0 mm (0 in.)
Transition Length
50.8 mm (2.0 in.)
6.35 mm (0.25 in.)
Gage Length
Long: 101.6 mm (4.0 in.)
Short: 76.2 mm (3.0 in.)
Extensometer
Bearing Points
UHP
FRC
Grip
Plate
152.4 mm (6.0 in.)
Wedge
Grip
127.0 mm
(5.0 in.)

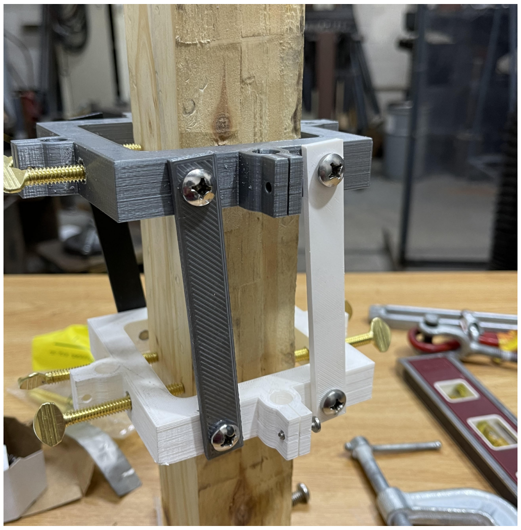

MTS

Based on the images provided in the paper by Graybeal, I began working out a similar model in AutoCAD to start.

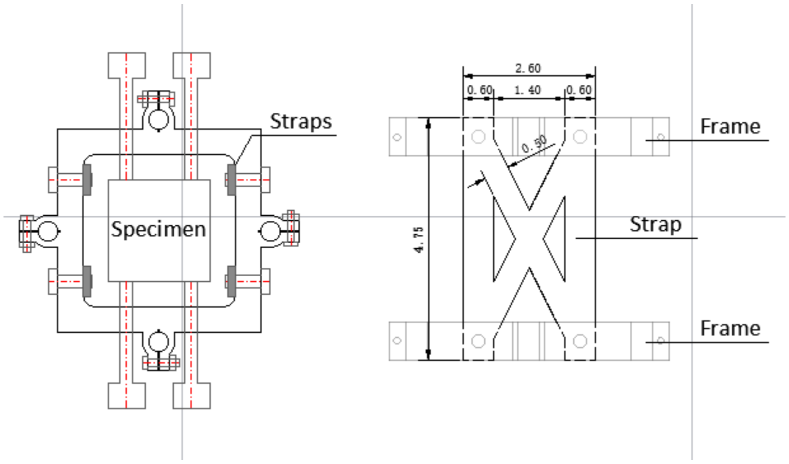




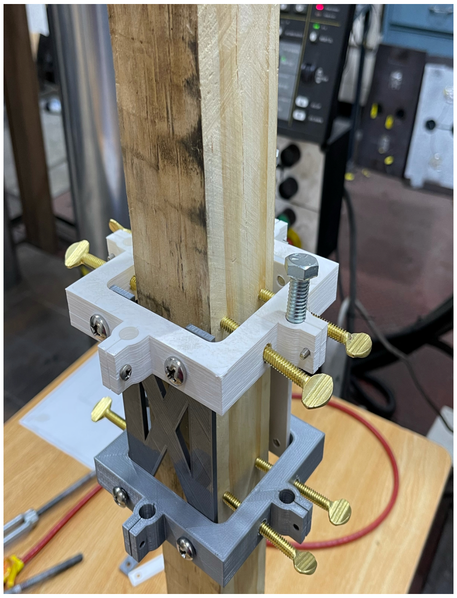
With the help of my Graduate mentor Huaian Zhang, we were able to reproduce this specification and I was able to model into AutoCAD as seen above in the rendering. The process went through several iterations, mainly stemming from the size of the screws. The original apparatus was twice as large, but needed to be scaled down to fit within the confines of the available 3D printers available at Wilbur Powerhouse. After the final design was completed, I was able to get the parts 3D printed with plastic with the material choose subject to change if needed. I was able to get a mock specimen cut into a 2x2x24 beam at ATLSS and assemble the apparatuses as seen below.



While the apparatuses were assembled correctly, the gauge straps were determined to be too unstable providing issues down the line so were slated to be disassembled and reconfigured.

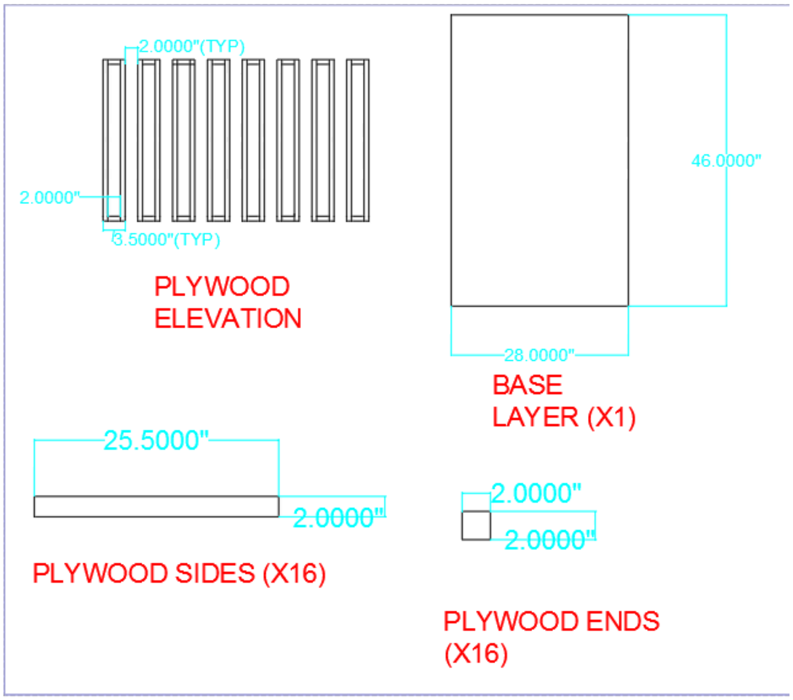


New straps were designed to be interconnected provided more stability to both the specimens and apparatuses.



After construction of the apparatuses was finally finished, concrete mix design as well as specimen design was next.

First I went about designing the forms to house our specimens. We originally wanted to construct a 2x2x17 specimen, as cited in the Graybeal paper but opted for a 2x2x24 specimen. Next, I went about designing a cut plan in AutoCAD with plywood sections to cast the concrete into.



After receiving the plywood, I assembled 8 plywood forms in total to house our specimens. I also received 2 ASTM 6x6x21 forms to cast our mix into for further testing.

With the forms in hand next came the mix design. Using an Excel spreadsheet compiling the available materials in the welding lab at ATLSS, I was able to produce a basic UHPC mix design using Water, Portland cement, No. 8 size stone, Aztec sand, Portland cement, slag, Silica Fume, SF Fiber, an Air entrainment agent, and Super Plasticizer. The Moisture content of the sand was taken to ensure the correct amount of water was used. After calculating the total volume needed, I came to a value of 2 feet cubed. This produced the mix seen below:

Water weight:			20.07	lb
Coarse aggregate weight(wet):			96.71	lb
Fine aggregate weight(wet):			113.64	lb

Portland Cement weight:			32.39506173	lb
Slag weight:			23.7037037	lb
Silica Fume weight:			3.160493827	lb
SF Fiber weight:			4.814814815	lb
AEA:			1.037037037	oz
HRWR:			4.740740741	oz

After the casting process of the first batch, we were able to cast all 8 forms, the 2 ASTM forms, and 10 4x8 cylinders for testing.

These will cure for a total of 28 days per the ASTM standards. The last batch performed on August 2nd produced 43 cylinders for testing with a total of 2.5 feet cubed in the mix.

Conclusion/ Future Plans

Due to the time constraints of this summer research experience and unforeseen circumstances due to COVID, I was not able to get into testing itself. Although I was not able to fully complete the project this summer, I have learned the process of doing research is long and often does not necessarily agree with your timeframe. I was still able to work on multiple projects unrelated to mine and gain valuable insight into different testing methods unlike the one related to my project. I was able to gain first hand experience in batching concrete well before I have actually gained the classroom knowledge on these topics. Through the research I had to do and practical application of both using CAD software and reading up on concrete, I feel I am well prepared and ahead of the curve in terms of my classes going forward in my Junior year. While I may have taken a lot of valuable material from this project in its infancy, a lot must been done in the coming weeks and months. The Direct Tension Test still needs to be performed on the various specimens under from strain 0 to failure. This will require not only time to collect data but also time to possibly creating more batches of cylinders and beams to repeat and validate findings.

REFERENCES

“Pennsylvania: ASCE's 2021 INFRASTRUCTURE Report Card.” ASCE's 2021 Infrastructure Report Card |, 13 July 2021, infrastructurereportcard.org/state-item/pennsylvania/.

Graybeal, Benjamin. “Development of Direct Tension Test Method for Ultra-High-Performance Fiber-Reinforced Concrete.” ACI Materials Journal, vol. 110, no. 2, Apr. 2013, pp. 177–186., doi:10.14359/51685532.

Tadros, Maher, et al. “Implementation of Ultra-HighPerformance Concrete in Long-Span Precast Pretensioned Elements for Concrete Buildings and Bridges.” EConstruct, 21 Jan. 2020, pp. 1–384., doi:10.15554/pci.rr.mat-012.

CIAMTIS
U.S. DOT Region 3 University Transportation Center

Investigation of the Benefit of Using a Novel Corrosion Resistant Steel in New and Existing Steel Bridges in Pennsylvania

August 6, 2021

Prepared by:
Alexis J. Javier, Lehigh University

r3utc.psu.edu

PennState
College of Engineering

LARSON
TRANSPORTATION
INSTITUTE

DISCLAIMER

Technical Report Documentation Page

1. Report No. [UTC assigned]	**2. Government Accession No.**	**3. Recipient's Catalog No.**

4. Title and Subtitle Investigation of the Benefit of Using a Novel Corrosion Resistant Steel in New and Existing Steel Bridges in Pennsylvania	**5. Report Date** August 6, 2021
	6. Performing Organization Code
7. Author(s) Alexis, J. Javier	**8. Performing Organization Report No.**
9. Performing Organization Name and Address ATLSS Engineering Research Center Department of Civil and Environmental Engineering Lehigh University 117 ATLSS Drive Bethlehem, PA 18015	**10. Work Unit No. (TRAIS)**
	11. Contract or Grant No. [Enter contract number here]
12. Sponsoring Agency Name and Address U.S. Department of Transportation Research and Innovative Technology Administration 3rd Fl, East Bldg E33-461 1200 New Jersey Ave, SE Washington, DC 20590	**13. Type of Report and Period Covered** Draft Final Report 06/02/2021 – 08/06/2021
	14. Sponsoring Agency Code

15. Supplementary Notes

[Enter sponsor contact's Name, Email, Phone]

16. Abstract

Corrosion of steel remains a significant cause of structural deterioration of bridges. It results in strength loss and crack susceptibility due to steel cross-section thinning from the creation of rust. Inspection and maintenance can cause significant economic costs to bridge owners and social costs for traffic users in the form of delays and congestion. A new type of corrosion resistant material known as ASTM A709-50CR (ASTM A1010) is explored due to its high resistance to atmospheric corrosion. Developed by ArcelorMittal, A709-50CR is able to endure in structures significantly longer compared to traditional carbon steel, nearly 100 to 125 years. More importantly, it does not require maintenance or repainting actions unlike carbon steel, avoiding traffic delays and maintenance costs. An existing road network located in Chester County, PA is analyzed to determine if replacing its steel bridges with A709-50CR is beneficial. By using transportation network analysis to find the user equilibrium traffic flows, social consequences of bridge failure can be determined. Then, using consequence and probability of failure, the risk of the bridge network associated with carbon steel and A709-50CR can be computed. Then, the benefit of replacement can be determined. Bridges can also be ranked for maintenance priorities based on this risk. For example, a bridge with high level of importance within the bridge network will be prioritized. Lastly, bridges can be ranked based on its individual risk of failure. The results indicate that A709-50CR can achieve economic benefit when used to replace bridges of the existing road network.

17. Key Words Innovative materials, A709-50CR, A1010, corrosion, steel bridges, transportation network analysis	**18. Distribution Statement** No restrictions. This document is available from the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 24	**22. Price**

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

Table of Contents

List of Figures

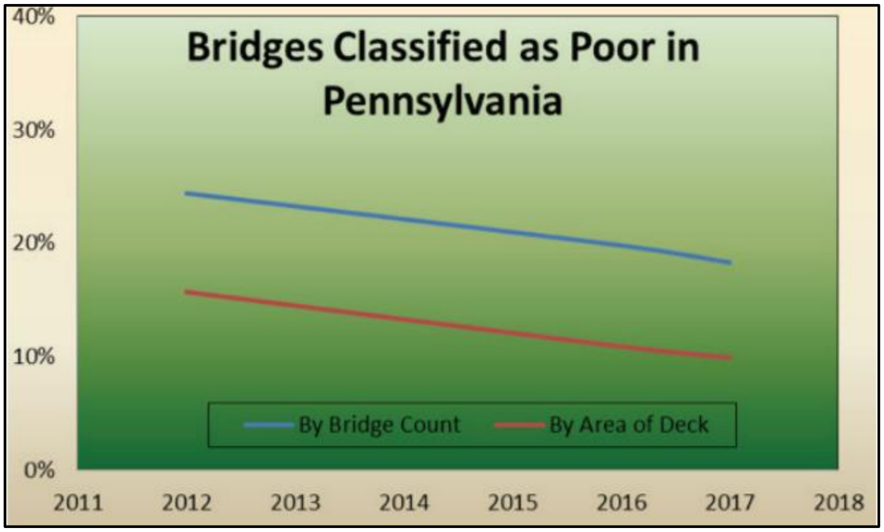
List of Tables

CHAPTER 1

Introduction

BACKGROUND

The United States has nearly 617,000 total bridges. However, a significant amount of these bridges continues to deteriorate and age, continually failing to meet design standards and leading to delayed and costly repairs. At least 42% of these bridges (260,000) are at least 50 years old and 7.5% of all bridges (46,000) are structurally deficient or contain a "poor" rating. Pennsylvania contains a significant amount of highway bridges, making the ninth largest inventory in the nation of about 22,779. The state contains even worse conditions of its bridge infrastructure compared to the average among the nation; 18.3% of its bridges are considered to be in poor condition (more than double the national average) according to the American Society of Civil Engineers' (ASCE) 2018 Pennsylvania Infrastructure Report Card (see Figure 1). Despite the national average bridge age of 43, Pennsylvania contains bridges of about 58 years on average. The average bridge age of solely poor rated bridges jumps up to 80 years, clearly beyond the age that its bridges were designed for. With climate change increasing the intensity and frequency of natural hazards, it is imperative to find innovative solutions to the nation's crumbling infrastructure.

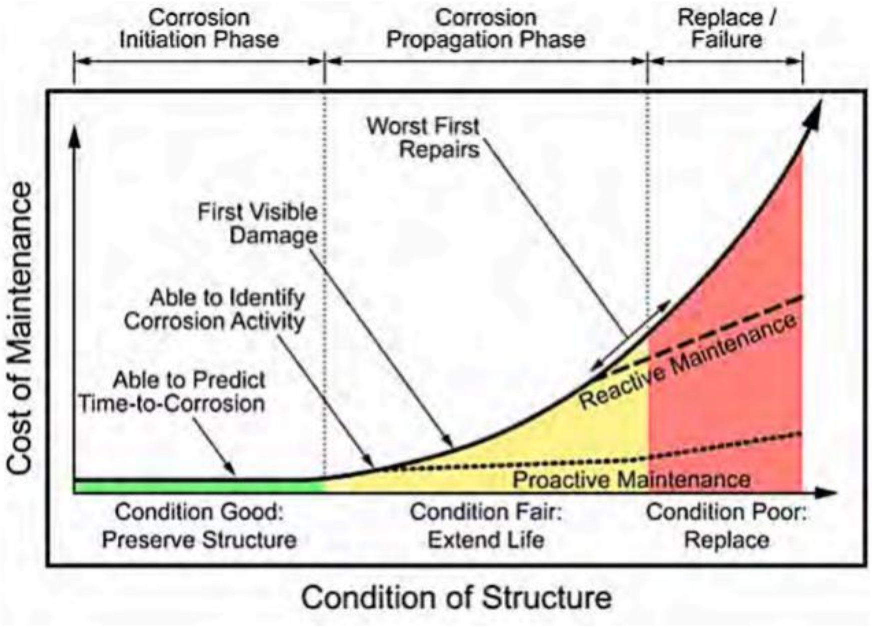


Source: American Society of Civil Engineers

Figure 1: *Percentage of Bridges Classified as Poor Condition in Pennsylvania*

Corrosion of steel remains a significant cause of structural deterioration of bridges. Corrosion of steel results in strength loss and crack susceptibility due to steel cross-section thinning from the creation of rust. Specifically, corrosion could cause a structure to not be able to fulfill its intended serviceability and strength requirements from a decrease in yield or buckling strength. Bridges located in coastal environments and areas exposed to deicing salts promote locally high rates of corrosion, prompting frequent inspection and maintenance actions to control the level of corrosion.

The issue of corrosion becomes especially important when considering the cost of repair and prevention. The National Association of Corrosion Engineers (NACE) estimates the annual cost of corrosion of highway bridges to be $13.6 billion. Corrosion repair becomes increasingly expensive as the degree of damage and cost caused by corrosion increases over time, along with the rate of increase as can be seen in Figure 2. Therefore, preventative measures such as barrier coatings, galvanizing, or metallizing is employed to slow down corrosion to prevent significant financial costs and potential structural failure. However, these particular methods can lead to considerable maintenance costs and traffic delays.



Source: National Association of Corrosion Engineers

Figure 2: *Bridge Condition and Cost of Maintenance as a function of time*

OBJECTIVES

A new type of corrosion resistant material known as ASTM A709-50CR (ASTM A1010) is explored due to its high resistance to atmospheric corrosion. Developed by ArcelorMittal, A709-50CR is able to endure in structures significantly longer compared to traditional carbon steel, nearly 100 to 125 years. More importantly, it does not require maintenance or repainting actions unlike carbon steel, avoiding traffic delays and maintenance costs.

An existing road network located in Chester County, PA is analyzed to determine if replacing its steel bridges with A709-50CR is beneficial. By using transportation network analysis to find the user equilibrium traffic flows, social consequences of bridge failure can be determined. Then, using consequence and probability of failure, the risk of the bridge network associated with carbon steel and A709-50CR can be computed. Then, the benefit of replacement can be determined. Bridges can also be ranked for maintenance priorities based on this risk. For example, a bridge with high level of importance within the bridge network will be prioritized. Lastly, bridges can be ranked based on its individual risk of failure.

CHAPTER 2

Methodology

The following figure is a summary of the methods used within this research (Figure 3). This chapter will describe each section in detail.

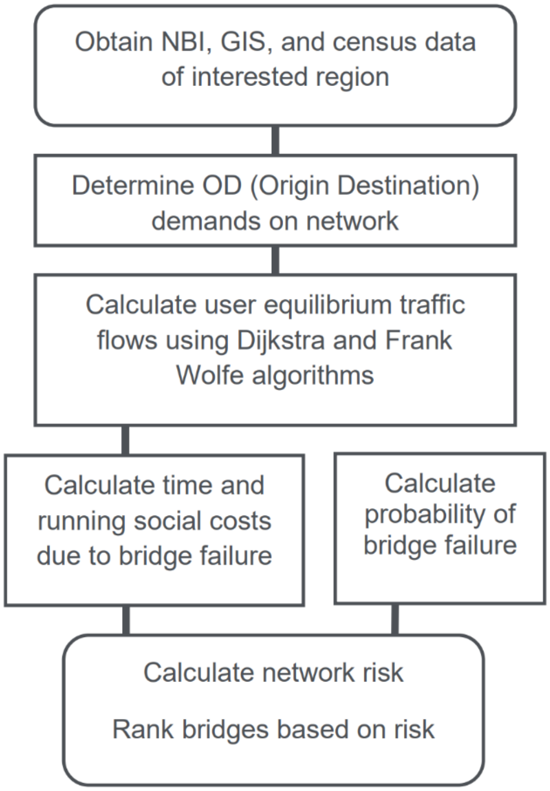


Figure 3: *Flowchart for risk-based bridge ranking under corrosion failure*

OBTAINING DATA OF INTERESTED REGION

The first step in this research is to determine a region of study. Choosing an appropriate region of study is important as it would allow for an easier analysis of the bridges within the network. The road network was chosen for its simplicity in geometry and the number of steel bridges present in the network. For example, the bridges in the road network are simply supported and straight, allowing for an easier analysis. Secondly, because A709-50CR is analyzed when replaced in steel bridges, an appropriate amount of steel bridges had to be present within the network. The road network features some concrete bridges, but for the purposes of this study, these were ignored during bridge ranking and replacement benefit.

The road network chosen is an existing highway bridge network, located in Chester County, Pennsylvania as shown in Figure 4. It consists of 22 highway segments (L1-L22), 10 bridges (B1-B10), and 8 nodes (N1-N8). Highways are modeled as network links, while nodes denote highway intersections, origins, or destinations.

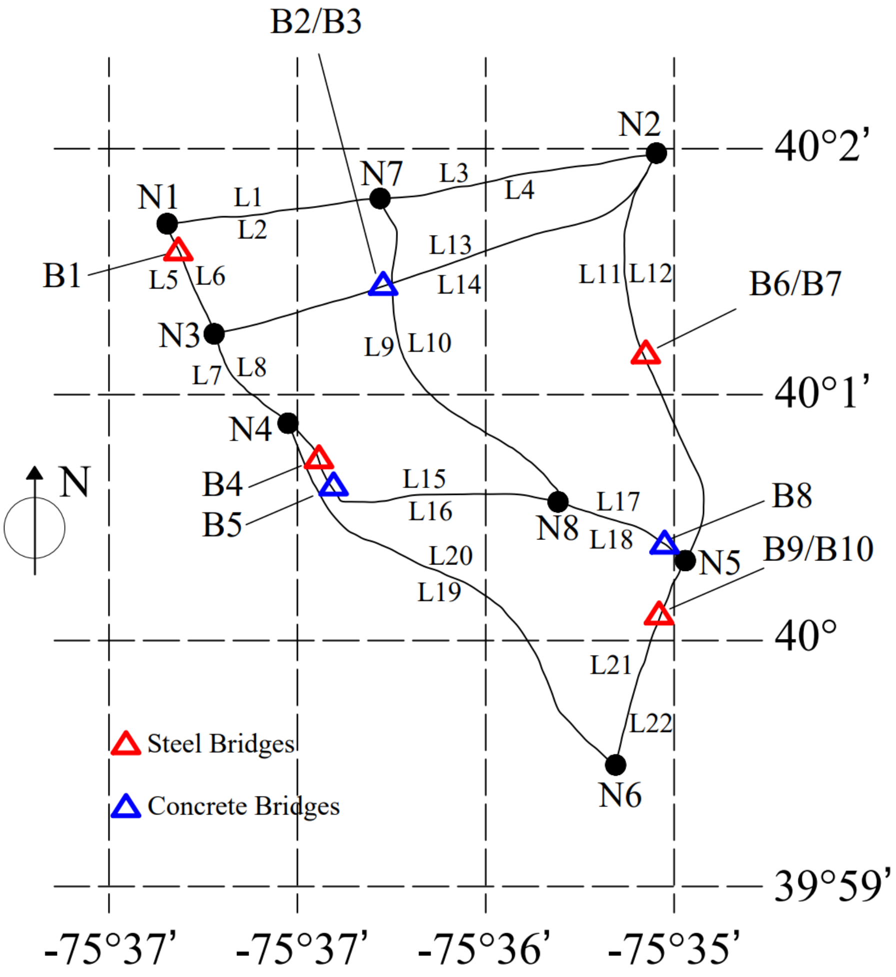


Figure 4: *Regional highway network in Chester County, Pennsylvania*

Once an appropriate road network has been identified, characteristics of the road network must be determined, as these are used in calculations of transportation network analysis and determination of probability of bridge failure. These characteristics such as bridge dimensions, location, superstructure type, and highway segment length are collected through the National Bridge Inventory (NBI). Secondly, census data used for transportation analysis is obtained from the Federal Highway Administration. This includes information such as annual average daily traffic (AADT) and average daily traffic (ADT). These characteristics are summarized in Table 1 and Table 2.

Table 1: *Bridge characteristics of highway network*

Bridge ID	Structural number (NBI)	Latitude	Longitude	Structure Type	Material	Length (m)	Width (m)	Years of service until 2020	AADT
1	10066	40.02769	-75.6278	Multi-girder	Steel	9.5	38.7	20	45,613
2	10003	40.02414	-75.6089	Multi-girder	Prestressed concrete	27.9	13.3	26	21,239
3	10001	40.02392	-75.6090	Multi-girder	Prestressed concrete	27.9	13.3	26	24,420
4	10060	40.01152	-75.6156	Multi-girder	steel	32.3	9.8	11	7,024
5	10402	40.00949	-75.6144	Box girder	Prestressed concrete	28.0	13.9	30	12,463
6	10112	40.01926	-75.5861	Multi-girder	steel continuous	35.7	13.4	22	22,830
7	10111	40.01936	-75.5859	Multi-girder	steel continuous	35.7	13.4	22	22,592
8	10403	40.00548	-75.5824	Box girder	Prestressed concrete	17.7	13.4	20	23,717
9	10109	40.00163	-75.5848	Multi-girder	steel	15.1	14.7	22	20,890
10	10108	40.00177	-75.5844	Multi-girder	steel	15.1	13.4	22	20,405

Table 2: *Highway segment characteristics*

Link number	First node	Second node	Free travel time (min)	Link length (km)	Critical capacity (cars/h)	Number of lanes	Free speed (km/h)
L1 , L2	N1	N7	1.3	1.60	4000	2	72
L3 , L4	N2	N7	1.8	2.12	4000	2	72
L5 , L6	N1	N3	0.7	0.89	16000	8	72
L7 , L8	N3	N4	0.6	0.75	8000	4	72
L9 , L10	N7	N8	3.2	2.96	4000	2	56
L11 , L12	N2	N5	2.2	3.31	8000	4	90
L13 , L14	N2	N3	2.5	3.69	8000	4	90
L15 , L16	N4	N8	3.1	2.91	4000	2	56
L17 , L18	N5	N8	1.2	0.82	4000	2	40
L19 , L20	N4	N6	2.3	3.49	8000	4	90
L21 , L22	N5	N6	1.4	2.09	8000	4	90

Each link pair has a link for one opposite direction of traffic. For example, link 1 contains traffic traveling from node 7 to node 1, while link 2 contains traffic traveling from node 1 to node 7. An important parameter used in transportation network analysis is critical capacity, or the practical capacity of a link containing the maximum traffic flow where road segment performance is still reasonable. Traffic which exceeds the practical capacity contains significant congestion. It is dependent on lane width, number of available lanes, speed limit, highway segment length, and other parameters. Typically, practical link capacity is assumed to be 2,000 car-equivalent vehicles per hour per lane. Therefore, bridge failure will reduce the capacity of a highway segment to a near-zero level, leading to alternate routes taken from traffic users.

DETERMINATION OF ORIGIN DESTINATION DEMANDS

The second step in this process is determining traffic demands on each origin and destination pair. Origin-destination (O-D) pairs represent number of travelers on a trip throughout the network from the origin node to the destination node. It is possible that multiple origins and destinations are present in the network, leading to a collection of OD pairs known as an O-D matrix. The O-D matrix includes the demand of traffic flow between each O-D pair. Census data, traffic counts, and the model considered by Fisk and Boyce (1983) are used to determine vehicle traffic per day throughout the network. The doubly constrained model used has the optimization formulation of:

$$\min_{g_{ij},h_{ijk}} \mu \sum_{a} \left[\int_{0}^{v_a} s_a(v) \cdot dv \right] + \sum_{ij} g_{ij} \cdot \ln(g_{ij})$$

$$\text{s.t} \begin{cases} \sum\limits_{j \neq i} g_{ij} = O_i & \forall i \quad (\alpha_i) \\ \sum\limits_{i \neq j} g_{ij} = D_j & \forall j \quad (\beta_i) \\ \sum\limits_{k} h_{ijk} = g_{ij} & \forall i, j \quad (\chi_{ij}) \\ v_a \quad = \sum\limits_{ijk} \delta_{ijk}^{a} \cdot h_{ijk} & \forall a \\ g_{ij} \ , h_{ijk} \geq 0 & \end{cases}$$

where for a given link a, the sum of all g_{ij} (OD-flows from i to j) traversing this link is the link volume, v_a; g_{ij} and h_{ijk} are the O-D flows; O_i and D_j are the number of travelers going from the i^{th} origin to the j^{th} destination , respectively; χ_{ij} is a Lagrange multiplier equal to the minimum costs for travel; and α_i and β_i are Lagrange multipliers that are determined so that the trip production and attraction constraints are fulfilled. An optimization algorithm is used to minimize this objective function to find the O-D demand matrix.

It was assumed that vehicles travel through a 14-hour period in the day. Additionally, vehicles in the traffic network were assumed to be cars and trucks. The vehicle demand data is divided into total vehicles and trucks traveling in the network, leading to two separate O-D matrices. The difference between the total vehicles on each link and the trucks on the link result to the volume cars traveling on the link. The O-D matrices used in this study can be found below.

Total traffic O-D Matrix (vehicles/day)

$$\begin{pmatrix} 0 & 3998 & 3133 & 1622 & 1841 & 7037 & 644 & 1155 \\ 3998 & 0 & 9398 & 4771 & 1984 & 12395 & 2273 & 2759 \\ 3133 & 9398 & 0 & 544 & 620 & 2395 & 1139 & 866 \\ 1622 & 4771 & 544 & 0 & 423 & 1619 & 584 & 583 \\ 1841 & 1984 & 620 & 423 & 0 & 1847 & 145 & 430 \\ 7037 & 12395 & 2395 & 1619 & 1847 & 0 & 2613 & 2587 \\ 644 & 2273 & 1139 & 584 & 145 & 2613 & 0 & 627 \\ 1155 & 2759 & 866 & 583 & 430 & 2587 & 627 & 0 \end{pmatrix}$$

Truck O-D Matrix (vehicles/day)

$$\begin{pmatrix} 0 & 213 & 290 & 45 & 16 & 998 & 220 & 9 \\ 213 & 0 & 1812 & 296 & 442 & 581 & 35 & 456 \\ 290 & 1812 & 0 & 11 & 4 & 262 & 12 & 22 \\ 45 & 296 & 11 & 0 & 13 & 907 & 2 & 78 \\ 16 & 442 & 4 & 13 & 0 & 50 & 60 & 38 \\ 998 & 581 & 262 & 907 & 50 & 0 & 43 & 50 \\ 220 & 35 & 12 & 2 & 60 & 43 & 0 & 67 \\ 9 & 456 & 22 & 78 & 38 & 50 & 67 & 0 \end{pmatrix}$$

Despite there being a presence of secondary or minor roads, it is assumed that traffic users only utilize highways, regardless of distance between O-D pairs. This is an acceptable assumption as this research deals with the ranking of highway bridges instead of focusing on the most accurate prediction of traffic flow. In addition, this leads to a simpler computation and analysis when determining user equilibrium traffic flows.

TRANSPORTATION NETWORK ANALYSIS

To determine the social consequences of bridge failure, the flow of vehicles on each link of the road network is determined through transportation network analysis. A model must be employed to estimate the flows that satisfies both demand and capacity. Some models minimize network travel time or travel distance, but for the purposes of this study, the principle of user equilibrium (UE) is employed to determine the flow of vehicles given link cost. This principle assumes that traffic users choose routes that minimizes their own travel costs and are well-informed about the road network. This eventually leads to an equilibrium of traffic flows in the road network. Travel or link costs are considered as the time it takes to travel a link. In this study, updated link costs given traffic conditions are determined through the Bureau of Public Roads equation as:

$$t_a(f_a) = t_{a,0}\left[1 + \alpha\left(\frac{f_a}{f_{a,c}}\right)^{\beta}\right]$$

where $t_a(f_a)$ is the updated travel time on link a; $t_{a,0}$ is the free speed travel time; f_a and $f_{a,c}$ is the flow and capacity of vehicles on link a, respectively; and α and β is 0.15 and 4, respectively.

Based on UE principle, the travel time of any traffic user cannot be reduced by switching to an alternative path. This can be modeled as a mathematical programming problem as follows (Bell and Iida 1997; Patriksson 2015):

$$\min T(\mathbf{f}) \triangleq \sum_{a\in\mathbb{A}} \int_0^{f_a} t_a(s)ds$$

subjected to

$$\sum_{r\in\mathbb{R}_{pq}} h_{pqr} = d_{pq} \quad , \quad \forall\,(p\,,q) \in \mathbb{C}\,,$$

$$h_{pqr} \geq 0 \quad , \quad \forall \;\; r \in \mathbb{R}_{pq} \quad , \; \forall\,(p\,,q) \in \mathbb{C}\,,$$

$$\sum_{(p\,,q)\in\mathbb{C}} \; \sum_{r\in\mathbb{R}_{pq}} \delta_{pqra} h_{pqr} = f_a, \;\; \forall\, a \in \mathbb{A}$$

where $\mathbb{A}$ is the set of all links; $\mathbb{C}$ is the set of OD pairs; $\mathbb{R}_{pq}$ is the set of paths between OD pq; h_{pqr} is the flow on path r between OD pq; d_{pq} is the traffic demand between OD pq; and δ_{pqra} is the link route matrix. The matrix contains an element of 1 if route r uses link a and a 0 otherwise.

This mathematical program can be solved using the Frank Wolfe algorithm. To improve the computational efficiency, the Dijkstra shortest-path algorithm was also used to update the shortest path given congestion or bridge failures. Details for both the Dijkstra and Frank Wolfe algorithm can be found in the appendix.

These programs are utilized to find the flows on the road network given no bridge failures and the traffic flow given failure of each bridge to be used in computing the social consequence of bridge failure.

CONSEQUENCE OF BRIDGE FAILURES

As mentioned, the failure consequences of bridge failures only consider the social cost in the road network; other costs such as rebuilding, or repair costs of a failed bridge are not considered. The social costs include extra travel time and extra travel distance that users must endure as a result of congestion from bridge failure. This will be referred to as time cost and running cost, respectively. The consequence of bridge failure is found by calculating the time and running costs for both cars and trucks. The summation of these two parameters yields the total social cost of bridge failure. The equations used to determine time and running costs are as follows (Decò and Frangopol 2011; Saydam et al. 2013b):

$$
\begin{gathered}
Cost_{time,car} = C_{AW} \cdot O_{car} \cdot (TTT_{cond} - TTT_o) \\
Cost_{run,car} = C_{run,car} \cdot (TTD_{cond} - TTD_o) \\
Cost_{time,truck} = (C_{ATC} \cdot O_{truck} + c_{good}) \cdot (TTT_{cond} - TTT_o) \\
Cost_{run,truck} = C_{run,truck} \cdot (TTD_{cond} - TTD_o)
\end{gathered}
$$

where $Cost_{time,car}$ and $Cost_{time,truck}$ are the time costs for cars and trucks, respectively; $Cost_{run,car}$ and $Cost_{run,truck}$ are the running costs for cars and trucks, respectively; TTT_{cond} and TTD_{cond} are the conditional total travel time (TTT) and total travel distance (TTD) of every vehicle given bridge failure; and TTT_o and TTD_o are the initial TTT and TTD without bridge failure. Other parameters used are summarized in Table 3 (Saydam et al. 2013a).

Table 3: *Parameters used in social consequence calculation given bridge failure*

Parameter	Description	Value
C_{AW}	Average wage of car drivers	22.82 USD/h
C_{ATC}	Average compensation of truck drivers	26.80 USD/h
O_{car}	Average vehicle occupancy of cars	1.50
O_{truck}	Average vehicle occupancy of trucks	1.05
$C_{run,car}$	Running cost of cars	0.08 USD/km
$C_{run,truck}$	Running cost of trucks	0.375 USD/km
c_{good}	Time value of cargo	4 USD/h

PROBABILITY OF BRIDGE FAILURES

First-order reliability method, or FORM, was used to find the probabilities of bridge failures over a 75-year period. FORM is an analysis method to estimate the reliability of structural systems. The road network is a system made of multiple layers, containing both series and parallel subsystems. A system in series has a failure probability of (Rackwitz and Krzykacz 1978):

$$P_f = 1 - \Phi_n(\beta; \mathcal{R}_Z)$$

where $\Phi_n(\,)$ is the standard multinormal integral with correlation coefficient matrix $\mathcal{R}_Z$; and β is the safety index. For parallel systems, the failure probability is:

$$P_f = \Phi_n(-\beta; \mathcal{R}_Z)$$

Secondly, to rank the bridges individually, the unconditional failure probabilities were found for the period 2021 to 2065. Then, the summation of these values yielded the individual failure probability for a bridge failure.

RISK ANALYSIS AND BRIDGE RANKING

After both the consequence of failure and probability of failure for each bridge is determined, the risk of failure for each bridge can be found. Risk is defined as the product of probability and failure consequence. The total risk for a bridge factoring in the time value of money is:

$$R = \sum_{i=N+1}^{N+45} \frac{P_{fi} \times Cost_f}{(1+r)^{i-N-1}}$$

where R is the risk associated with a bridge; P_{fi} is the unconditional failure probability of a bridge in year i; $Cost_f$ is the social cost of a failed bridge; r is the discount rate of assumed to be 2%; and N is the existing service life of a bridge. Bridges are assumed to contain an additional service life of 45 years considering its existing service life (*N*) since it was last repaired. Thus, the bridges are analyzed from a period of 2021 to 2065.

Once risk is obtained for each, bridges are ranked based on their network level risk for maintenance priority. That is, bridges with a high level of risk of failure have a higher level of importance within the network, and therefore are prioritized to prevent failure. Secondly, bridges can also be ranked by its individual failure probability, related to the structural condition. This is a second ranking that analyzes the importance of bridges individually, instead of the network. Finally, by comparing the risk of a bridge made of traditional steel and of A709-50CR, the benefit of implementing A709-50CR can be seen.

CHAPTER 3

Findings

RESULTS AND DISCUSSION

Total traffic time (TTT) and total traffic distance (TTD) were calculated for no bridge failures, and for each bridge failure. An example of the total travel time given failure of bridge B1, and failure of no bridge can be seen in the following table.

Table 4: *Total travel time (TTT) on links given no failure and B1 failure*

Links	1,2	3,4	5,6	7,8	9,10	11,12	13,14	15,16	17,18	19,20	21,22
No Failure	27.8	27.5	31.9	34.4	4.8	90.6	84.4	19.2	16.5	90.64	65.74
B1 Failure	60.6	106.3		16.3	13.6	151.0	123.0	10.7	16.5	27.7	91.9

When B1 has failed, links 5 and 6 are correspondingly removed from the network, hence the greyed cell. Most links saw a significant increase in their total travel time, indicating considerable congestion as a result from bridge failure. Given TTT and TTD, social consequence per year for failure of each steel bridge was found. This can be seen in the following Figure 7.

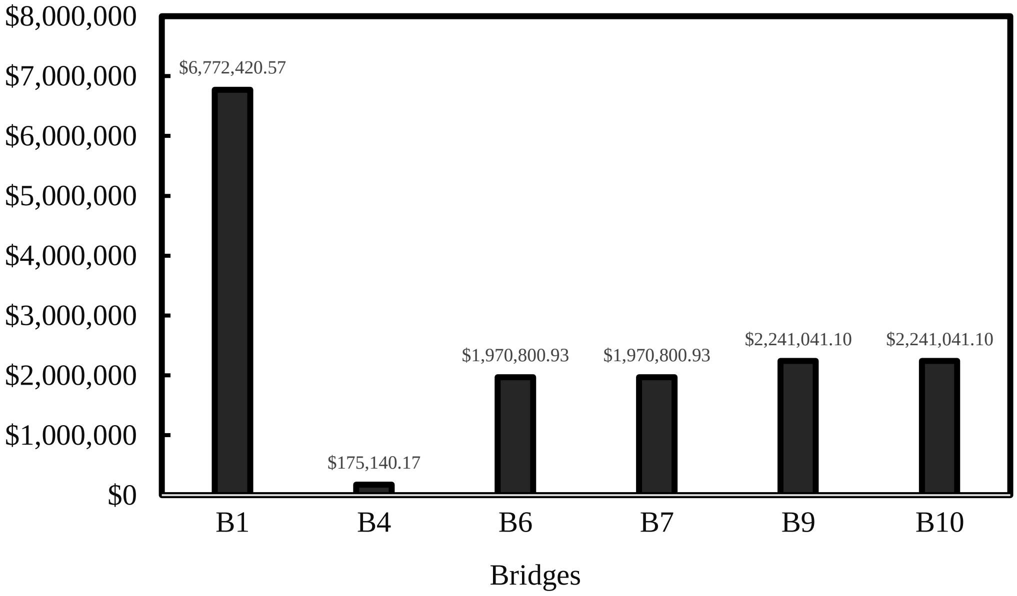


Figure 5: *Annual Consequence of Failure (USD)*

Because of the relatively high amounts of vehicle traffic traveling through bridge B1, it contains the highest social consequence for failure. This is consistent with the fact that bridge B1 failure causes the greatest amount of detour and congestion in other roads. Bridge B4 contains the lowest social consequence for failure do to that fact that when it fails, traffic on adjacent highways is not affected significantly. Bridges B6, B7, B9, and B10 have moderate consequences for failure.

Secondly, unconditional failure probability from year 2021 to 2065 was found for each steel bridge, as shown below.

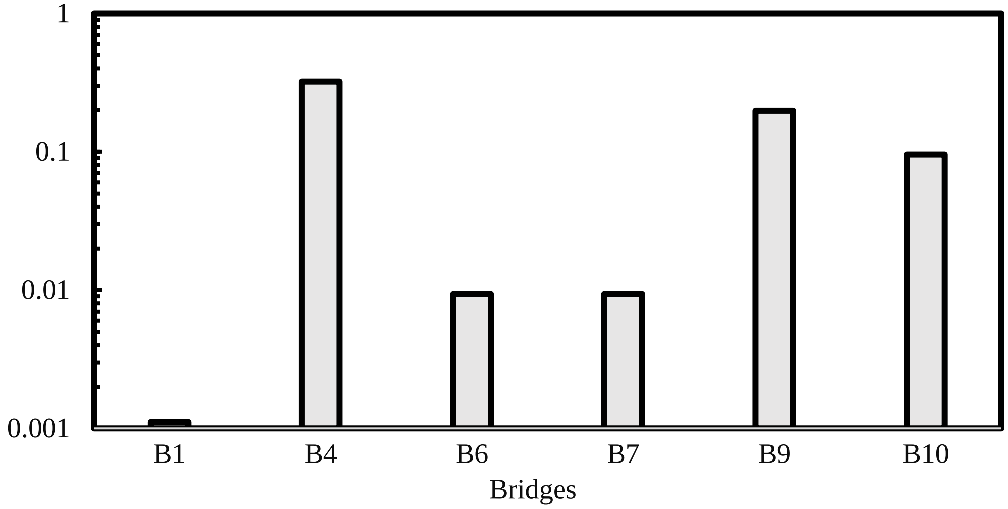


***Figure 6:** Probability of Failure during the period 2021-2065*

It can be seen from Figure 8 that bridge B1 has a very low probability of failure. If a bridge has a large consequence for failure, engineers will ensure it does not fail, hence its low probability. Similarly, B4 has a significant probability of failure. However, as mentioned previously, its social cost of failure is relatively low considering it does not contain substantial traffic within the road network. Bridges B9 and B10 have moderate probabilities of failure.

With consequence and failure calculated, risk of failure of each bridge from year 2021 to 2065 can be found.

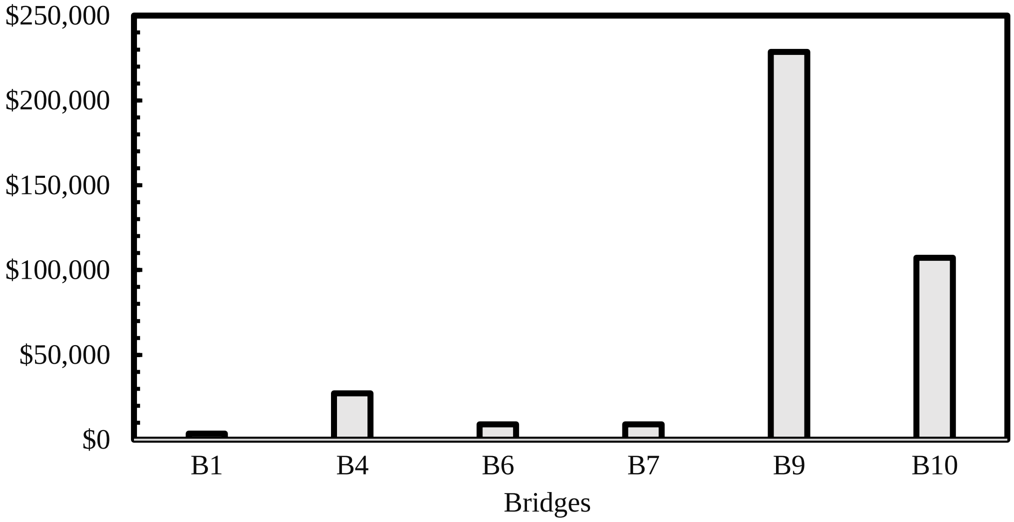


***Figure 7:** Risk of failure during the period 2021-2065*

It can be seen that despite having the highest consequence for failure, B1 contains the lowest risk because of its significantly low probability of failure. Similarly, bridges B6 and B7 contain low risk because of its relatively low probability of failure. B4 contains higher risk than bridges B1, B6, and B7. Although it has the lowest social consequence, it has the highest probability of failure — thus, containing a higher risk. Bridge B9 contains the highest risk of failure, attributed to its moderate social consequence and high probability of failure. Bridge B10 contains a similar case for its risk.

The ranking of bridges both on the network and individually can be now determined. This can be seen in Figure 10.

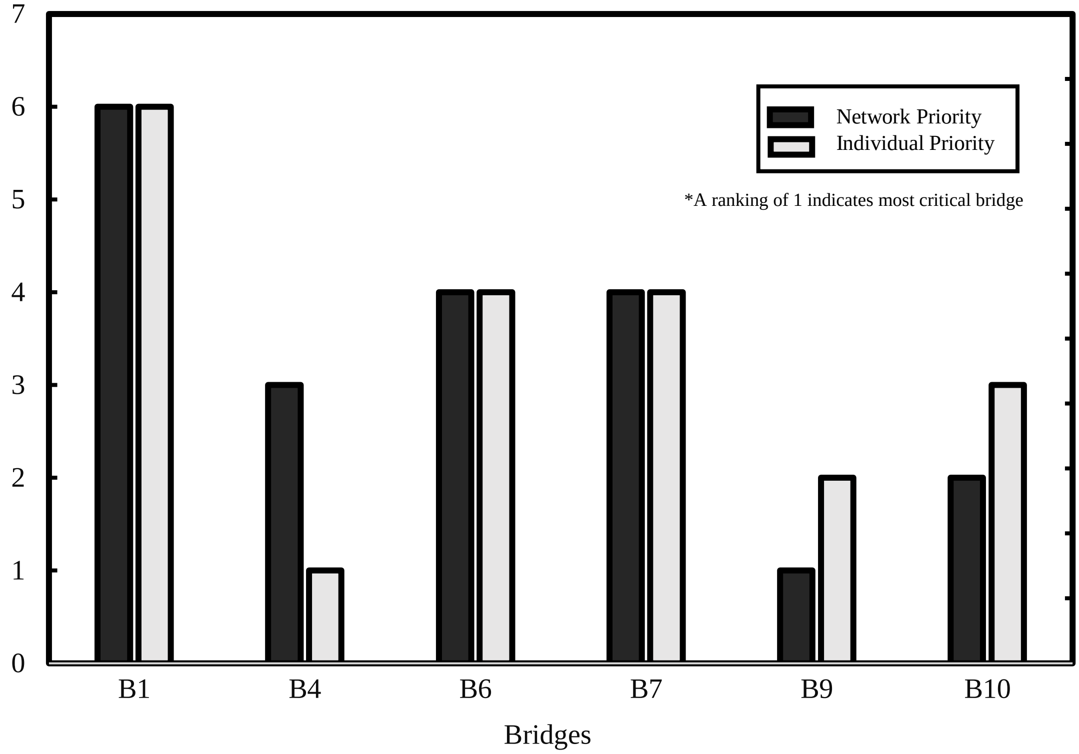


Figure 8: *Bridge ranking based on different performance metric*

As mentioned previously, because of B1's low risk, it ranks the lowest of all bridges, and therefore, should not be prioritized for maintenance. Similarly, B4 contains the largest probability of failure, but due to its low consequence of failure, it contains a low ranking for maintenance priority. B9 and B10 have moderate consequences of failure, but relatively high probabilities of failure and therefore, should be considered the most critical for maintenance priority. B6 and B7 have moderate consequences and probability of failure, so it ranks relatively low for maintenance priority.

Finally, the relative benefit of implementing A709-50CR as a replacement in the steel bridges can be seen by comparing the risk of the bridges made of traditional steel and of A709-50CR. The results are shown in the following Table 4.

Table 5: *Benefit of steel bridges replaced with A709-50CR*

Bridge	B1	B4	B6	B7	B9	B10
Benefit (2021 USD)	3,576	27,299	8,633	8,633	226,034	106,776

Most bridges do not need to be considered for replacement with A709-50CR. However, B9 and B10 are an exception. Because they contain high risk of failure, replacement with A709-50CR will yield the greatest benefit.

CONCLUSION

In this study, a corrosion resistant steel, A709-50CR, is investigated to determine its benefits when used to replace existing steel bridges in a road network located in Chester County, Pennsylvania. A method is proposed to rank maintenance priority and benefit of replacement. This approach only considers the social benefits based on the detour and congestion caused by individual bridge failure. The Fisk and Boyce model is used to determine the OD demands of the network. FORM is used to estimate failure probabilities of bridge failures and consequence of failure is found based on the total travel time and total travel distance of vehicles in the highway transportation network. Transportation network analysis is employed to analyze changes in route choices of traffic users to determine social costs of bridge failure. Some conclusions can be drawn:

- When a bridge in the network fails, the detour of traffic users leads to additional user cost. Different bridges are associated with different failure consequences, depending on the location and other characteristics of the bridges in the network.
- Risk ranking of a bridge in the network is contingent upon both the failure probability profiles and failure consequences.
- Different metrics used in the ranking processes can lead to different ranking results.

Appendix

DIJKSTRA'S SHORTEST PATH ALGORITHM

The Dijkstra algorithm is used to find the lowest cost between a start node and every other node in a graph. It produces a connections matrix and a backnode matrix. The connections matrix indicates the values of the least costs from start node to every other node. If ***N*** is the number of nodes and ***Z*** is the number of centroids, the matrix has ***N*** + ***Z*** rows and columns. The backnode matrix produces a matrix that indicates the penultimate node on the path from a start node to every other node. The size of the backnode matrix is the same as the connections matrix. The pseudocode for Dijkstra's shortest path is:

```
function Dijkstra(map, source)
      for each vertex v in map       //   Initialization
      dist[v] =infinity              //   Initial distance from start node to
                                          vertex is set to infinity
      previous[v] = undefined        //   Previous node in shortest path
      dist[source] = 0               //   Distance from source to source is 0
      Create vertex set Q            //   The set of all nodes in map
      while Q is not empty
         u = vertex in Q with min dist[u]
         remove u from Q
         for each neighbor v of u:   //   only v that are still in Q
            alt = dist[u] + length(u,v)
            if alt < dist[v]
            dist[v] = alt
            prev[v] = u
      return dist[], prev[]
end
```

FRANK-WOLFE ALGORITHM

The following details the specific steps of the Frank-Wolfe algorithm (Yang and Frangopol 2018; Patriksson 2015):

Step 0: *Initialization*. Initialize $\mathbf{f}^{(0)}$ as a feasible solution, e.g., AON (all or nothing) assignment; lower bound *LBD* = 0; convergence criteria $\varepsilon > 0$; and iteration number k = 0.

Step 1: *Search direction generation*. Let

$$\bar{T}(\mathbf{f}) \triangleq T\left(\mathbf{f}^{(k)}\right) + \nabla T\left(\mathbf{f}^{(k)}\right)^{T}\left(\mathbf{f} - \mathbf{f}^{(k)}\right)$$

Solve the linear programming subproblem

$$\min \bar{T}(\mathbf{f})$$

Subjected to

$$\sum_{r \in \mathbb{R}_{pq}} h_{pqr} = d_{pq} \quad , \quad \forall\, (p\,,q) \in \mathbb{C}\,,$$

$$h_{pqr} \geq 0 \quad , \quad \forall \;\; r \in \mathbb{R}_{pq} \quad , \; \forall\, (p\,,q) \in \mathbb{C}\,,$$

$$\sum_{(p\,,q) \in \mathbb{C}} \sum_{r \in \mathbb{R}_{pq}} \delta_{pqra} h_{pqr} = f_a, \quad \forall\, a \in \mathbb{A}$$

Let $\mathbf{y}^{(k)}$ be its solution, and $\mathbf{p}^{(k)} = \mathbf{y}^{(k)} - \mathbf{f}^{(k)}$ the resulting search direction.

Step 2: *Convergence check*. Let $LBD = \max\left\{LBD, \bar{T}\left(\mathbf{y}^{(k)}\right)\right\}$. If

$$\frac{T\left(\mathbf{f}^{(k)}\right) - LBD}{LBD} < \varepsilon$$

then terminate, with $\mathbf{f}^{(k)}$ as the approximate solution. Otherwise, continue.

Step 3: *Line search*. Find a step length $l^{(k)}$, which solves the one-dimensional problem

$$\min\left\{T\left(\mathbf{f}^{(k)} + l^{(k)}\mathbf{p}^{(k)}\right) \mid 0 \leq l^{(k)} \leq 1\right\}$$

Step 4: *Update*. Let $\mathbf{f}^{(k+1)} = \mathbf{f}^{(k)} + l^{(k)}\mathbf{f}^{(k)}$.

Step 5: *Convergence check*. If

$$\frac{T\left(\mathbf{f}^{(k+1)}\right) - LBD}{LBD} < \varepsilon$$

then terminate, with $\mathbf{f}^{(k+1)}$ as the approximate solution. Otherwise, let $k = k + 1$, and go to Step 1.

POSTER PRESENTATION

Investigation of the Benefit of Using Novel Corrosion Resistant Steel (A709-50CR) in New and Existing Steel Bridges In Pennsylvania

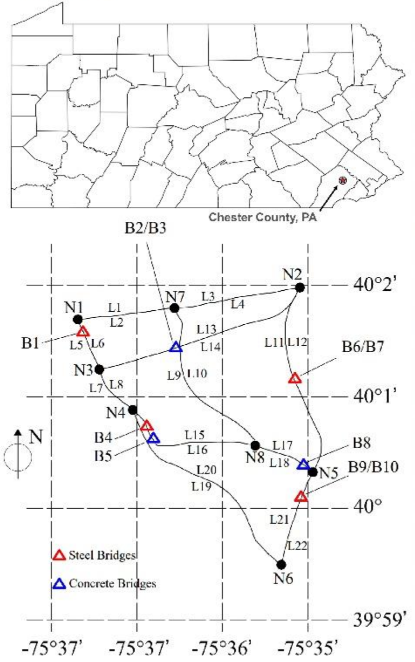
RESEARCHERS

Faculty:
Dr. Dan Frangopol, Lehigh University
Undergraduate(s):
Alexis Javier, Lehigh University
Graduate Students:
Xu Han, Lehigh University

Background

According to ASCE's 2018 Pennsylvania Infrastructure Report Card, amidst more than 22,780 highway bridges in the state, nearly 18.3% are in poor condition. Notably, Pennsylvania's bridges are 15 years older than the national average and continue to deteriorate. Corrosion of steel remains a significant cause of this structural deficiency. Steel corrosion can lead to costly repairs and potential structural failure. A new type of corrosion resistant steel, A709-50CR, is investigated to determine if replacing an existing carbon steel bridge network is beneficial. By determining the risk of an existing bridge network associated with carbon steel and A709-50CR, the benefit of this type of steel can be determined. In addition, bridges can be ranked for maintenance priorities based on this risk.

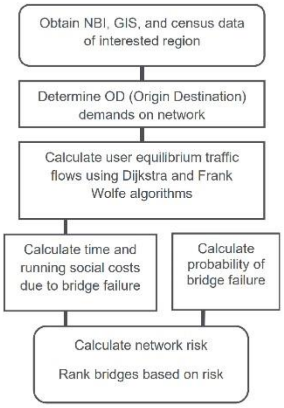
Network Map



Bridge Information

B1	Multi-girder	Steel
B2	Multi-girder	Prestressed Concrete
B3	Multi-girder	Prestressed Concrete
B4	Multi-girder	Steel
B5	Box girder	Prestressed Concrete
B6	Multi-girder	Steel continuous
B7	Multi-girder	Steel continuous
B8	Box girder	Prestressed Concrete
B9	Multi-girder	Steel
B10	Multi-girder	Steel

Methods



Obtain NBI, GIS, and census data of interested region

Determine OD (Origin Destination) demands on network

Calculate user equilibrium traffic flows using Dijkstra and Frank Wolfe algorithms

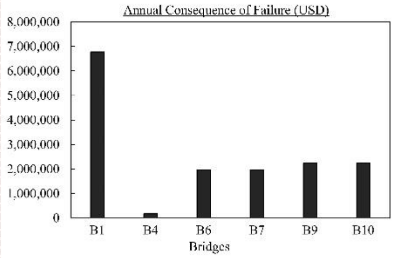
Calculate time and running social costs due to bridge failure

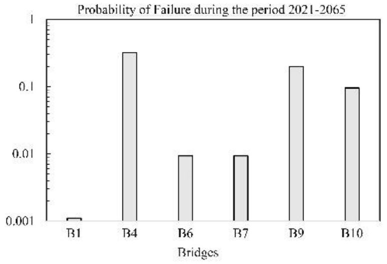
Calculate probability of failure

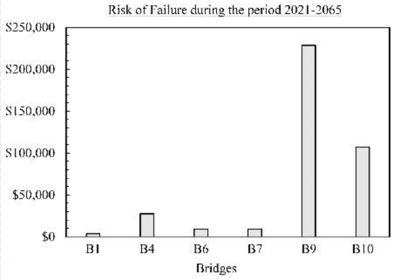
Calculate network risk

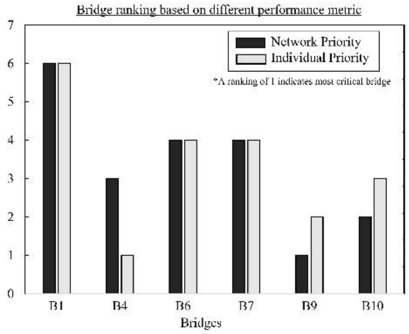
Rank bridges based on risk

Results


Annual Consequence of Failure (USD)


Probability of Failure during the period 2021-2065


Risk of Failure during the period 2021-2065


Bridge ranking based on different performance metric

Benefit of Steel Bridges replaced with A709-50CR

Bridge	B1	B4	B6	B7	B9	B10
Benefit (2021 USD)	3,576	27,299	8,633	8,633	226,034	106,776

- Despite B1 having the largest consequence for failure, due to its low probability of failure, its risk is extremely low and therefore, should not be prioritized for maintenance
- Similarly, B4 contains the largest probability of failure, but due to its low consequence of failure, it contains a low ranking for maintenance priority
- B9 and B10 have moderate consequences for failure, but relatively high probabilities of failure and therefore, should be considered most critical for maintenance priority
- B6 and B7 have moderate consequences and probability of failure, so it ranks relatively low for maintenance priority
- Bridges with highest risk of failure yield the greatest benefit of replacement with A709-50CR, particularly B9 and B10.

Conclusion

In this study, a corrosion resistant steel, A709-50CR, is investigated to determine its benefits when used to replace existing steel bridges in a road network located in Chester County, Pennsylvania. The approach only considers the social benefits based on the detour and congestion caused by individual bridge failure. Transportation network analysis was employed to analyze changes in route choices of traffic users to determine social costs of bridge failure. Bridges were also ranked for maintenance priority. Some conclusions can be drawn:

1. When a bridge in the network fails, the detour of traffic users leads to extra user cost. Different bridges are associated with different failure consequences, depending on the location of bridges in the network.
2. Risk ranking of a bridge in the network is contingent upon both the failure probability profiles and failure consequences.
3. Different metrics used in the ranking processes can lead to different ranking results.

References

ASCE's 2021 Infrastructure Report Card |. (2016). *Pennsylvania | ASCE's 2021 Infrastructure Report Card.* [online] Available at: https://infrastructurereportcard.org/state-item/pennsylvania/ [Accessed 29 Jul. 2021].
Han, X., Yang, D.Y. and Frangopol, D.M., 2021. Risk-based life-cycle optimization of deteriorating steel bridges: Investigation on the use of novel corrosion resistant steel. *Advances in Structural Engineering*, 24(8), pp.1668 1686.
Liu, L., Frangopol, D.M., Mondoro, A. and Yang, D.Y., 2018. Sustainability-informed bridge ranking under scour based on transportation network performance and multiattribute utility. *Journal of Bridge Engineering*, 23(10), p.04018082.
Yang, D.Y. and Frangopol, D.M., 2018. Risk-informed bridge ranking at project and network levels. *Journal of Infrastructure Systems*, 24(3), p.04018018.

Contact: ajj222@lehigh.edu | (914) 343 - 8840

Acknowledgement

This project was financed in part by a grant from the Commonwealth of Pennsylvania, through the Department of Community and Economic Development and the Pennsylvania Infrastructure Technology Alliance (PITA) program and by a grant from the U.S. Department of Transportation's University Transportation Centers Program through the Center for Integrated Asset Management for Multimodal Transportation Infrastructure Systems.

References

ASCE’s 2021 Infrastructure Report Card |. (2016). *Pennsylvania | ASCE’s 2021 Infrastructure Report Card*. [online] Available at: https://infrastructurereportcard.org/state-item/pennsylvania/ [Accessed 29 Jul. 2021].

Bell, M. G. H., and Y. Iida. 1997. Transportation network analysis. New York: Wiley.

C.S. Fisk and D.E. Boyce (1983), A note on trip matrix estimation from link traffic count data, Transportation Research 17B.

Decò, A., and D. M. Frangopol. 2011. “Risk assessment of highway bridges under multiple hazards.” J. Risk Res. 14 (9): 1057–1089. https://doi.org/10.1080/13669877.2011.571789.

Han, X., Yang, D.Y. and Frangopol, D.M., 2021. “Risk-based life-cycle optimization of deteriorating steel bridges: Investigation on the use of novel corrosion resistant steel*”*. Advances in Structural Engineering, *24*(8), pp.1668-1686.

Liu, L., Frangopol, D.M., Mondoro, A. and Yang, D.Y., 2018. “Sustainability-informed bridge ranking under scour based on transportation network performance and multiattribute utility.” Journal of Bridge Engineering, *23*(10), p.04018082.

NACE (2013) Highways and bridges. Available at: https://www.nace.org/resources/industries-nace-serves/highways-bridges (accessed July 2021).

NACE International (2012) *Corrosion Control Plan for Bridges*. Houston, TX: National Association of Corrosion Engineers (NACE).

Patriksson, M. 2015. “The traffic assignment problem: Models and methods.” Mineola, NY: Dover Publications.

R. Rackwitz and B. Krzykacz, Structural reliability of reactor systems. Probabilistic Analysis of Nuclear Reactor Safety, Vol. 3, Topical Meeting, May 1978, Los Angeles, pp. X8-X11.

Saydam, D., D. M. Frangopol, and Y. Dong. 2013b. “Assessment of risk using bridge element condition ratings.” J. Infrastruct. Syst. 19 (3): 252–265. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000131.

Yang, D.Y. and Frangopol, D.M., 2018. “Risk-informed bridge ranking at project and network levels.” Journal of Infrastructure Systems, *24*(3), p.04018018.

Acknowledgments

I am grateful for the support and guidance from Dr. Dan Frangopol, faculty mentor, and Mr. Xu Han, graduate student mentor. Firstly, many thanks to Dr. Frangopol for providing me with this position and giving me a chance to participate in the STEM-SI program. I want to thank Mr. Xu Han for his continued support and guidance throughout the duration of the program. He was extremely patient and helpful when I had many questions and was confused. He was always available late at night or early in the morning for meetings. I thank both of them for their support. I would also like to thank the financial support received from the U.S Department of Transportation Region 3 University Transportation Center. Thank you to all of my peers who participated in the program and made it a memorable time. Lastly, I would like to thank Lehigh University for providing me the opportunity to receive an education, ATLSS staff and graduate students for their warm welcome, and Dr. Chad Kusko and Dr. Richard Sause and the rest of the STEM-SI faculty for their efforts in creating the program. Their help is herein acknowledged.