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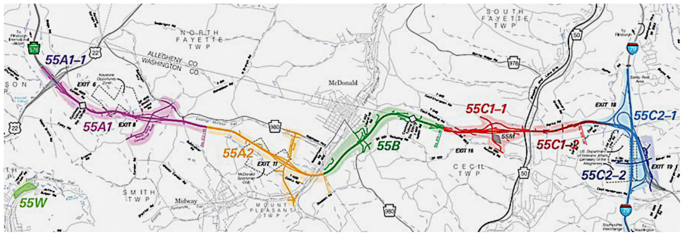

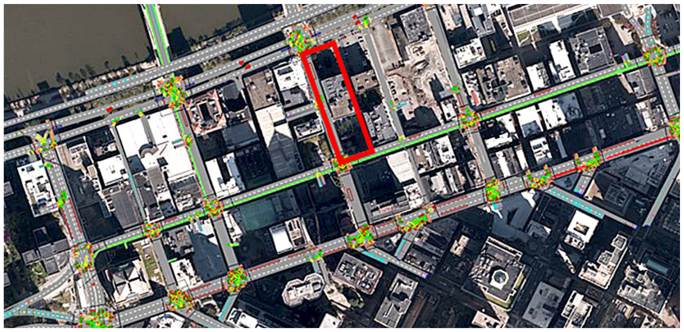

Developing Methodologies to Predict and Quantify the Benefits of Research that Creates Durable and Longer Lasting Highway Infrastructure

FINAL REPORT

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16. Abstract

This report provides the results of the benefit analysis for the five projects performed by IRISE. The first task performed as part of this research effort was a literature review. Current methodologies were evaluated to predict changes in highway infrastructure relative to longevity and resulting cost reductions due to innovations resulting from research. These existing methodologies, novel methods or new practices that were developed were considered for IRISE research projects based upon successful and meaningful results. Each of the projects was examined in detail to determine what types of unique benefits may be expected. It was determined that the benefits can be quantified based upon direct and indirect impacts. The benefits were documented to be significant. Based upon case studies performed reduced costs were projected in an individual project basis. Cost savings based upon overall project costs in Pennsylvania for related construction items were also substantial.

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Developing Methodologies to Predict and Quantify the Benefits of Research that Creates Durable and Longer Lasting Highway Infrastructure

November 28, 2022

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IRISE

The Impactful Resilient Infrastructure Science & Engineering (IRISE) consortium was established in the Department of Civil and Environmental Engineering in the Swanson School of Engineering at the University of Pittsburgh to address the challenges associated with aging transportation infrastructure. IRISE is addressing these challenges with a comprehensive approach that includes knowledge gathering, decision making, material durability and structural repair. It features a collaborative effort among the public agencies that own and operate the infrastructure, the private companies that design and build it and the academic community to develop creative solutions that can be implemented to meet the needs of its members. To learn more, visit: https://www.engineering.pitt.edu/irise/.

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Disclaimer

The views and conclusions contained in this document are those of the authors and should not be interpreted as representing official policies, either expressed or implied, of the Pennsylvania Department of Transportation, the Pennsylvania Turnpike Commission, the Allegheny County Department of Public Works, Golden Triangle Construction, the Constructors Association of Western Pennsylvania, CDR Maguire or Michael Baker International.

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Introduction

The transfer of new technologies into practice is the ultimate goal of research. Research to create more durable and longer lasting highway infrastructure has the objective of creating benefits to extend the life of highways and bridges that must be measured decades into the future. However, it is difficult to quantify and predict benefits for many of these advancements. This is due to the extended time frame and nature of the changes to realize the benefits in terms of user costs, capital costs and maintenance costs. Also, many of these benefits may be realized in the design and construction phases of highway infrastructure projects.

The purpose of this research project was to investigate methodologies to quantify research results and apply these to five research projects completed by IRISE.

The first task performed as part of this research effort was a literature review. Current methodologies were evaluated to predict changes in highway infrastructure relative to longevity and resulting cost reductions due to innovations resulting from research. These existing methodologies, novel methods or new practices that were developed were considered for IRISE research projects based upon successful and meaningful results.

During the next task, each of the five projects was examined in detail to determine what types of unique benefits may be expected. It was determined that the benefits can be quantified based upon direct and indirect impacts. Impact areas considered for each project included:

- Direct Economic Benefits
- Highway User Secondary Impacts
- Sustainability Considerations
- Scale of Research Impacts

After adoption of the strategies to quantify the benefits for each of the five projects, the benefits were determined. This was accomplished by collecting data on baseline conditions for each type of highway improvement under current designs or procedures and projecting benefits with implementation of the results. The quantification was performed on case studies and universal data sets depending upon the type of research project and availability of data.

Literature Review

The literature review was conducted to provide a baseline of current research and practices on the quantification of research results for highway infrastructure if outcomes were to be implemented by government agencies that are responsible for the infrastructure.

AASHTO (American Association of State Highway Transportation Officials) provides some guidance on how to quantify the benefits of improvements to highway infrastructure through their publication “User and Non-User Benefit Analysis for Highways, 3rd Edition 2010”. This document has been accepted by state Departments of Transportation (DOTs) to evaluate benefit/cost ratios for different applications and options for highway improvements.

This established publication was reviewed along with other manuals and research results that provide guidance. Because of the nature of much of the research conducted by IRISE, which addresses very specific problems with a novel design or construction innovation, these methodologies may not be applicable. A comprehensive literature review was compiled, considering the types of projects to be assessed, with a recommendation to use and/or develop a new methodology to fit these IRISE projects.

The literature review was based upon current academic research and Department of Transportation (DOT) policies and guidance on the topics. In addition, the types of benefits determined from this review are categorized for future consideration related to the development of specific methodologies for each of the six research projects to be evaluated in the next task.

I. Academic Research

Academic research for highway infrastructure typically is performed to develop novel methods to improve the design, construction, and maintenance of highway infrastructure such as highway features and systems. While it is implied that if the successful research results are implemented it will result in benefits to public agencies and users of the systems, often these potential benefits are not quantified.

However, some researchers have developed methods or applied the principals of engineering economics to project these benefits. These benefits could be for individual highway features such as pavements, bridges, or other ancillary components of a highway. The benefits could also apply to an entire highway system which may include economic, environmental and user benefits.

This summary of current academic research on benefit methodologies was developed to establish options available for application to IRISE projects.

1. Highway Systems Research Benefits

A highway system includes many components that research results can improve the longevity or durability. When implemented these improved components will contribute to the overall system state. When evaluating the impact of individual components of a highway the ultimate result would be a system that lasts longer, has reduced future maintenance costs, and minimizes impacts on users and the environment. This part of the literature review focused on methodologies that predict system benefits.

The review includes research that has been conducted on a larger scale to consider overall system benefits which many times considers user benefits.

Benefits of MnROAD Phase-II Research [Worel et al. 2015] report provides a comprehensive analysis of how to quantify highway research outcomes into benefits. This includes methodologies for many different projects that were completed during the MnROAD Phase-II research efforts. Various approaches to benefits analysis were formulated and they are direct, indirect, avoidance and demonstration of benefits outcomes. Benefits of some of the studied projects included:

- Extended asphalt pavement life due to delayed and reduced rate of temperature cracking occurrence and reduction in damage
- Improved pavement life due to development of stable, drainable aggregate base
- Optimized designs using thin and ultrathin concrete overlays of asphalt pavement
- Improvements to pavement life cycle and cost-effectiveness using recycled, unbound pavement materials
- Development of durable and low-noise pavement through innovative and ultimate grind surface textures
- Demonstration of a viable technique for the design of asphalt pavement rehabilitation using full-depth reclamation stabilized with engineered emulsion
- Reductions in construction delay by performing field investigation of aggregate base material stabilized with high-carbon fly ash
- Validation of network designs through detailed instrumentation and monitoring of pervious/porous pavements

- Validation of optimum concrete pavement thickness designs
- Successful demonstration of pavement preservation surface treatments on high-volume roadways

This report illustrated a broad approach to quantifying benefits of research work on highways systems. It provides an in-depth guide to methodologies. For specific highway features, such as pavements, the actual methodologies were examined in more detail in the following section under highway features.

The research project, Probabilistic Methodology to Quantify User Delay Costs for Urban Arterial Work Zones [Dolama et al. 2020] quantifies the user delay cost (UDC) for urban arterial work zones through traffic microsimulation and Monte Carlo simulation which in turn enables a network-wide estimate of travel delay for work zones in an urban highway network. The probabilistic methodology developed in this paper helps to determine the UDC distribution that can apply to multiple projects following the quantification of road user delay for each project. The document also provides the probability distribution of the risk associated with UDCs and thus helps to optimize work zone configuration, justify accelerated construction methods, and establish contractual incentives. User benefits are a type of benefit that may apply to some types of system or individual feature research results. This demonstrates one method of quantifying the benefit of reduced construction time for the traveling public.

To identify the impact of transportation projects on individuals, this research, A New Framework for Addressing High-level Decisions Related to Sustainable Transportation Development incorporates the dynamic index for national advancement (DINA) framework to quantify sustainable development [Warith et al. 2019] was reviewed. The DINA framework was particularly inspired by John Stuart Mill’s Utilitarianism*,* and his various other works as well as Jeremy Bentham’s, A Fragment on Government and An Introduction to the Principles of Morals and Legislation. It could be applied to different types of political entities as the framework regarded the problem solver as the governing body.

The calculations involved economic, environmental, and social engines in order to run the dynamic simulation model. The “happiness” component as the overarching objective and it is split into the project divisions of time and money which is proved to be a useful concept in the framework’s practicality. This is a tool that can address benefits from overall system changes due to improved highway components.

An integrated approach is proposed through this research, Sustainability and Resilience in The Rehabilitation of Road Infrastructures After an Extreme Event: An Integrated Approach [Guinta 2017] which includes a method to estimate sustainability in monetary terms as well as the resilience of a given highway rehabilitation alternatives after an extreme event such as earthquake, floods, and landslides. The life cycle cost analysis was applied to determine the sustainability whereas the resilience depended on an accurate estimate of reconstruction cost, user cost, and environmental costs in order to compare the alternatives. This is a tool to compare alternatives that may involve innovative solutions. Figure 1 from the report depicts how both sustainability and resilience benefits are considered.

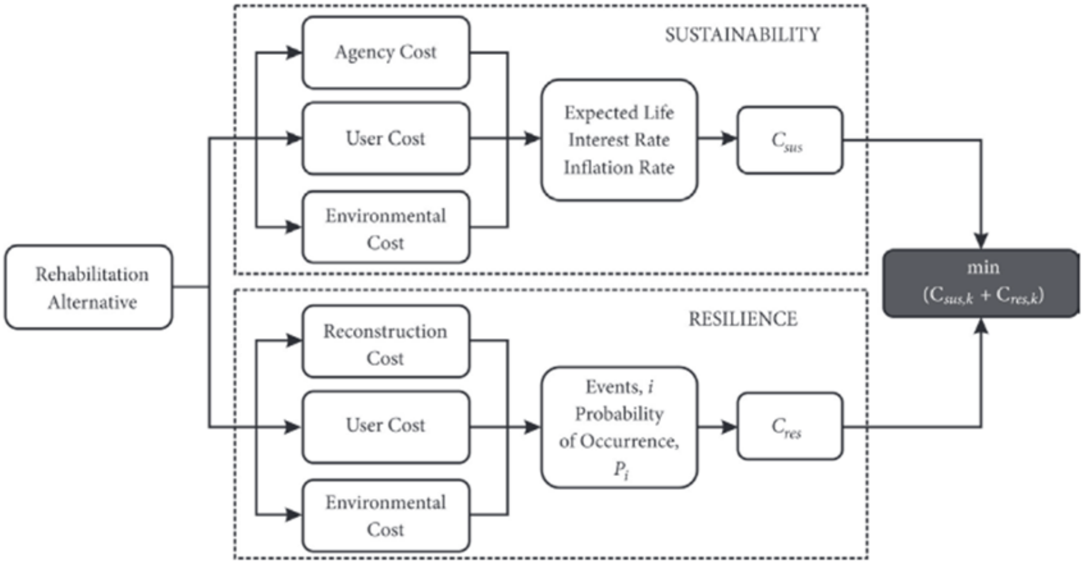


Figure 1: Extreme Event Integrated Approach to Benefit Analysis

Source: Guinta, “Sustainability and Resilience in the Rehabilitation of Road Infrastructure After an Extreme Event: An Integrated Approach”, 2017

The result of this investigation, Contradictory Outcomes of Cost-benefit Analyses – Findings from Norwegian Public-investment Projects [Bardal 2020] concerns issues related to contradictory outcomes of cost-benefit analyses (CBA) methods based on Norwegian public-investment projects. The study suggests that CBA can never be a complete description of matters under consideration as the appraisals of a project have a larger impact on the final result. Six important factors were identified that explain the impact of an appraisal on the outcomes of a project:

- Monetizing of investment costs
- Types of benefits measures
- Methodology used for measuring benefits

- Methods/standards used for valuing benefits
- Project-specific assumptions
- Whom had ordered the appraisals?

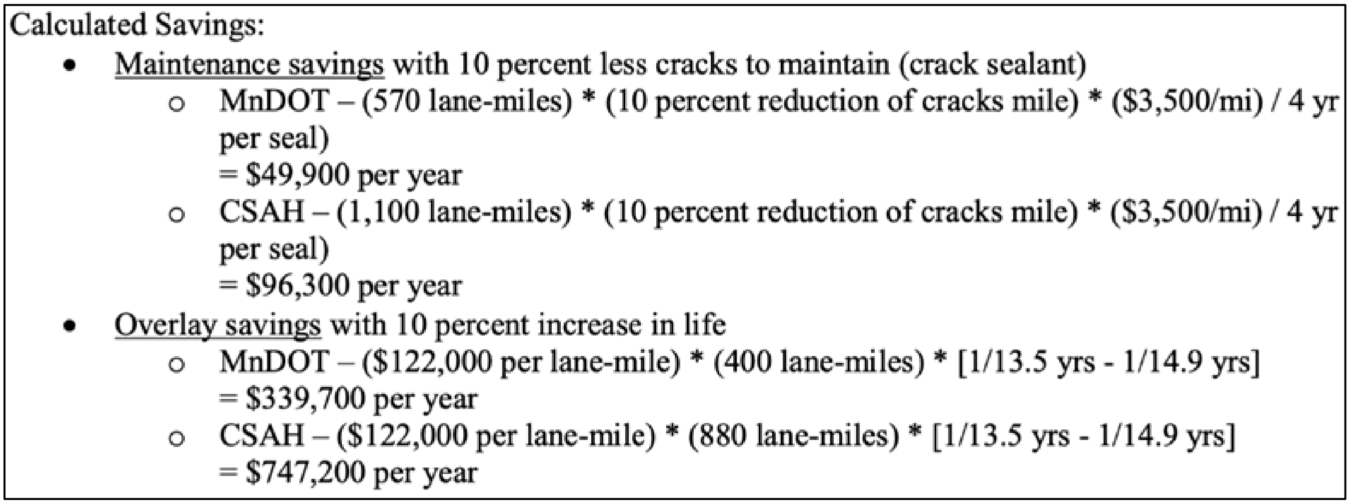
This research provided a critique of methods for conducting a benefit/cost analysis, concluding that results will vary based upon the methods and standards selected.

2. Highway Features Research Benefits

Individual features of a highway system such as pavements, drainage structures, and bridges are the components that much research focuses on to improve longevity resulting in reduced capital and maintenance costs. Many of the methodologies developed for benefit quantification focus on these individual components. Because the individual research results that were developed by IRISE focus on pavements and safety this research considered those components. The result was novel and potentially applicable methods to determine benefits when results are applied.

Benefits of MnROAD Phase-II Research [Worel et al. Appendix A] report also identified specific research project outcomes and detailed how the benefits were calculated. One project of interest “Investigation of Low Temperature Cracking in Asphalt Pavements” was how low temperature cracking (LTC) in asphalt pavements can be mitigated. To mitigate this problem and to improve the asphalt pavement life, the research developed a system to select appropriate asphalt mixtures by investigating different laboratory procedures, material properties and pavement features. The anticipated benefits from this study included maintenance savings, overlay savings and new/reconstruction cost savings. The study demonstrated the calculation for the cost benefits to MnDOT and the County State Aid Highway (CSAH) system.

The research provided an insight into the benefit calculation by assuming various modest performance increase scenarios such as 20 percent increased pavement life for new roadways,10 percent reduction in maintenance costs for existing roads, and 10 percent increase in resurfacing life for overlays These percentage increases in pavement life were translated into reduced future maintenance costs for crack sealing maintenance overlays and new paving. The calculations only considered costs for the most recent year data was available as shown in Figure 2.



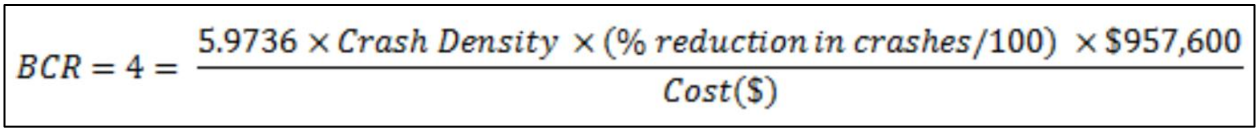
Calculated Savings:

- Maintenance savings with 10 percent less cracks to maintain (crack sealant)
    - MnDOT – (570 lane-miles) * (10 percent reduction of cracks mile) * ($3,500/mi) / 4 yr per seal)
      = $49,900 per year
    - CSAH – (1,100 lane-miles) * (10 percent reduction of cracks mile) * ($3,500/mi) / 4 yr per seal)
      = $96,300 per year
- Overlay savings with 10 percent increase in life
    - MnDOT – ($122,000 per lane-mile) * (400 lane-miles) * [1/13.5 yrs - 1/14.9 yrs]
      = $339,700 per year
    - CSAH – ($122,000 per lane-mile) * (880 lane-miles) * [1/13.5 yrs - 1/14.9 yrs]
      = $747,200 per year

Figure 2: MnRoad Asphalt Research Low Temperature Cracking Benefit Calculations

Source: Worel, “Benefits of MnROAD Phase-II Research 2015”

Quantifications of Safety Benefits Resulting from Road Smoothing 2012 on the other hand explored the relationship between crash risk, road geometry and road roughness parameters through the use of statistical modelling [Cenek et el. 2012] in New Zealand (NZ). Benefit-Cost Analysis was also used to determine the crash densities threshold for smoothing treatment to become a cost-effective maintenance intervention as shown in Figures 3 and 4. Various assumption had been made while BCA was being conducted for a period of 8 years.



$$BCR = 4 = \frac{5.9736 \times Crash\ Density \times (\%\ reduction\ in\ crashes/100) \times \$957,600}{Cost(\$)}$$

Where:

BCR = Benefit-Cost Ratio, 4 was the standard target used for small construction projects

5.9736 = the Uniform Series Present Worth Factor (USPWF) for a time period of 8 years

Crash Density = The reported injury crashed per year per 20 meters required to generate NZ $4 benefits for every NZ $1 spent

% reduction in crashes = Reference the graph (Figure 3) that shows the effect of change in International Roughness Index (IRI) on crash rate

$957,600 = 1.14 x $840,000 = The cost per reported injury crash ($ July, 2009) occur mid-block on 100 km/h remote rural roads with reference to New Zealand Transport Agency's Economic Evaluation Manual

Figure 3: Road Smoothing Benefit-Cost Analysis Calculations

Source: Cenek, *Quantification of Safety Benefits Resulting from Road Smoothing,* 2022

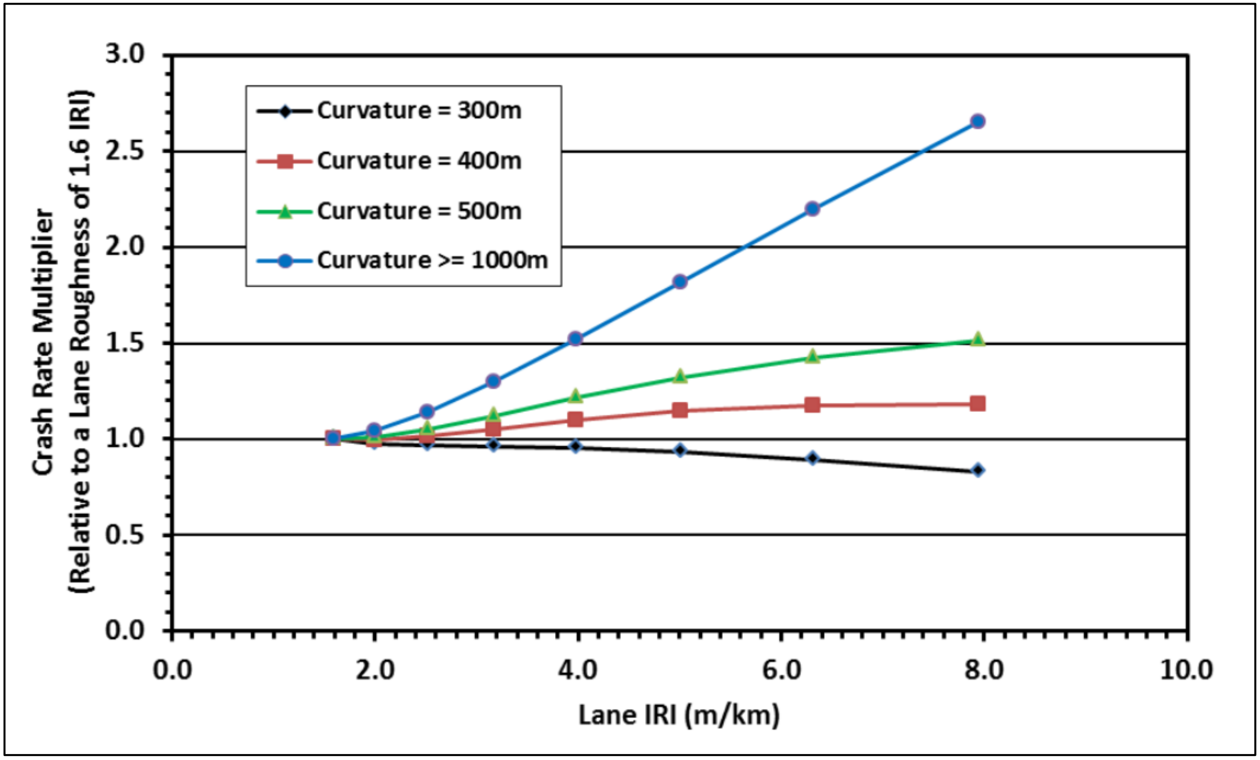


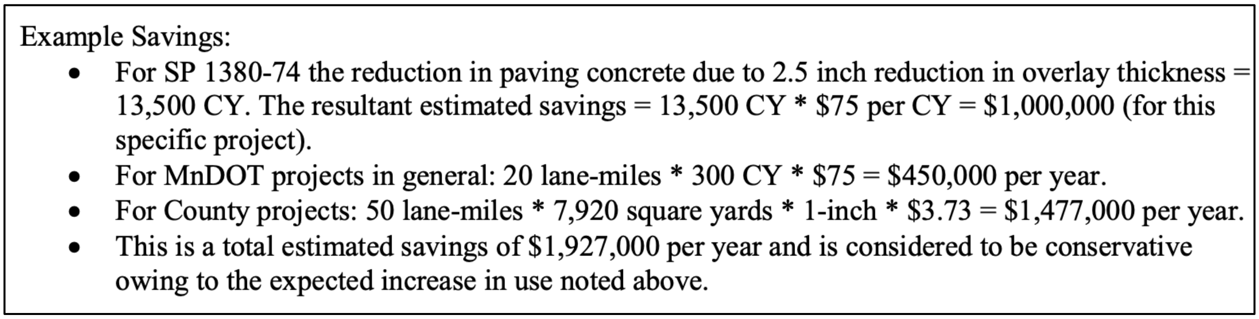
Figure 4: Effect of Change in Roughness on Crash Rate

Source: Cenek, *Quantification of Safety Benefits Resulting from Road Smoothing*, 2022

The aforementioned equation is a tool to formulate a benefit-cost ratio for research implementation. This formula only considers one year of benefits, crash reductions, crash density, and compares it to the BCR in order to estimate the total annual cost of the pavement improvement recommended by the research.

Benefits of MnROAD Phase-II Research [Worel et al. Appendix B] also examined the research project "Development of Design Guide for Thin and Ultrathin Concrete Overlays of Existing Asphalt Pavements ". The guide developed from this project aimed to create a standard design procedure for thin and ultrathin bonded concrete overlays of asphalt pavements (BCOA).

The results also demonstrated the benefits to MnDOT by calculating the savings the agency could benefit from the overlay thickness reduction from construction material savings shown in Figures 5 and 6.

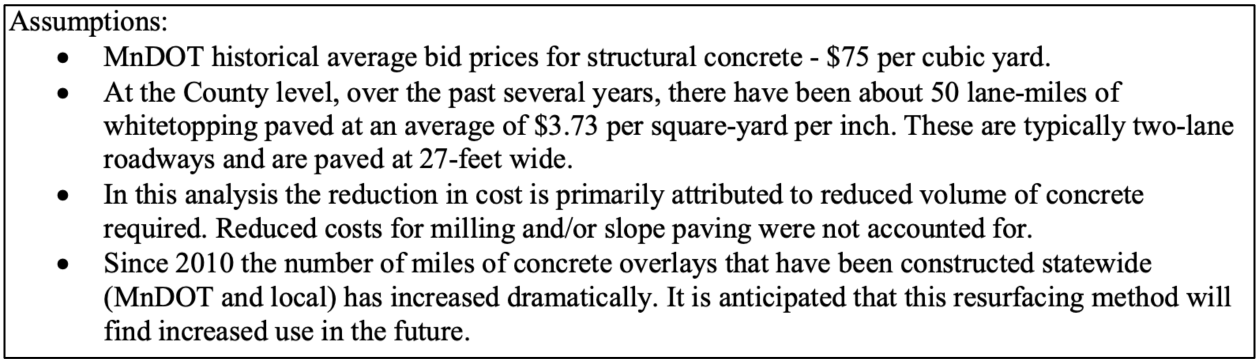


Example Savings:

- For SP 1380-74 the reduction in paving concrete due to 2.5 inch reduction in overlay thickness = 13,500 CY. The resultant estimated savings = 13,500 CY * $75 per CY = $1,000,000 (for this specific project).
- For MnDOT projects in general: 20 lane-miles * 300 CY * $75 = $450,000 per year.
- For County projects: 50 lane-miles * 7,920 square yards * 1-inch * $3.73 = $1,477,000 per year.
- This is a total estimated savings of $1,927,000 per year and is considered to be conservative owing to the expected increase in use noted above.

Figure 5: Savings Calculations for Thin and Ultrathin Concrete Overlays

Source: “Benefits of MnROAD Phase-II Research”, 2015



Assumptions:

- MnDOT historical average bid prices for structural concrete - $75 per cubic yard.
- At the County level, over the past several years, there have been about 50 lane-miles of whitetopping paved at an average of $3.73 per square-yard per inch. These are typically two-lane roadways and are paved at 27-feet wide.
- In this analysis the reduction in cost is primarily attributed to reduced volume of concrete required. Reduced costs for milling and/or slope paving were not accounted for.
- Since 2010 the number of miles of concrete overlays that have been constructed statewide (MnDOT and local) has increased dramatically. It is anticipated that this resurfacing method will find increased use in the future.

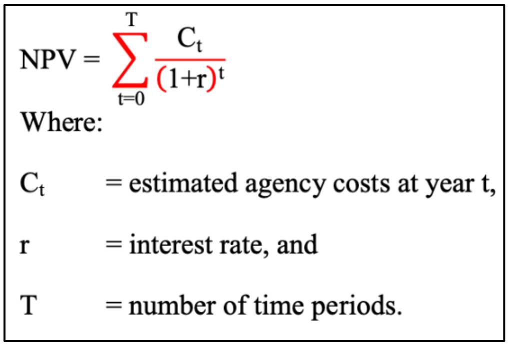
Figure 6: Assumptions made for the Savings Calculations

Source: “Benefits of MnROAD Phase-II Research”, 2015

The example savings demonstrated a method that considers construction cost savings applied to total annual paving costs for both the state and local highway agencies.

Binder Grade Bumping and High Binder Content to Improve Performance of RAP- RAS Mixtures 2018 was another identified research that quantified the improved performance and increased cost benefits from the utilization of binder-grade bumping and higher binder content strategies in recycled asphalt pavements (RAP) and recycled asphalt shingles (RAS) mixture production based in Oregon [Coleri et el. 2018].

The investigation started with the development of mechanistic-empirical (ME) pavement models for asphalt mixtures with different RAP and RAS content. Then the Life-Cycle Cost Analysis (LCCA) was conducted using the service lives for pavement structures obtained from the resulting ME models and different material costs combinations of various RAP content, binder content, and binder type. The LCCA was calculated by finding the Net Present Value (NPV) of the total agency costs which includes the 4 percent interest rate for a 50-year analysis period or the 5 percent interest rate for determining the sensitivity of cost effectiveness to different interest rates. Final step includes the salvage value in terms of NPV and added it to the NPV of the agency costs as shown in Figure 7.



$$NPV = \sum_{t=0}^{T} \frac{C_t}{(1+r)^t}$$

Where:

C_t = estimated agency costs at year t,

r = interest rate, and

T = number of time periods.

Figure 7: The Net Present Value Calculations for the Total Agency Costs

Source: Coleri et el., “Binder-Grade Bumping and High Binder Content to Improve Performance of RAP-RAS Mixtures”, 2018

The benefit calculations are a more advanced method when compared to the other examples because it considers the service life of research implementation as well as the present value based upon an assumed discount rate. This type of analysis is more of a typical engineering economic analysis.

The Scotland-based investigation, Assessment of the Economic Impacts of Landslides and Other Climate-Driven Events [Winter et el. 2012] looked into the consequences of climate-driven events such as landslides and floods on the road network. The economic impacts were categorized into three groups:

- Direct economic impacts: Clean-up costs, reconstruction costs, search and rescue costs
- Direct consequential economic impacts: Travel delay costs (road closures), and fatal/non-fatal casualties as well as accidents costs
- Indirect consequential economic impacts: Affected travel network that consequently affect travel-dependent activities. For an example, the short and long-term travels would be affected and thus resulting in reduced tourists or limited access to market and so forth

The impacts assessed by the study primarily were concerned with linear infrastructures, such as roads and highways. The methodology went beyond just direct economic benefits by also quantifying secondary benefits such as travelers and business reduction costs.

This MnDOT research [Worel et al. Appendix C] report identified the project “Optimal timing of preventive maintenance for addressing environmental aging in HMA pavements” which was conducted to determine the ideal period for when a preventive maintenance treatment should be implemented in order to mitigate asphalt aging damage. The research also aimed to improve the life cycle costs and pavement performance by identifying the asphalt aging factors as well as the optimal timing of preventive maintenance.

The results did not appear to have quantified the cost savings from the extended pavement life due to the preventive measures. Yet, the research results showed that MnDOT had applied chip seals as pavement preservation to higher volume roadways as a way to extend life cycle. The research concluded that the optimal time equaled one year after initial construction, the chip seal methodology helped MnDOT to reduce construction cost and thus fewer user delays. Even though the research did not manage to determine the cost savings benefits from longer life cycle, the paper had led insights into alternative preventive maintenance treatments that allow the public agency to reduce its reconstruction from two to one over the span of few years.

The research, “Life Cycle Thinking-Informed Approach to Support Pavement Design Decision Making” [Bhat et el. 2020] presented a method based on life cycle thinking that allows for this explicit type of analysis. It had also extended the boundaries of the problem to identify related parameters that can be used to determine most optimal solutions where all three objectives are considered. The three objectives are: cost, performance, and environment. An illustration of the method is provided for the design of a benchmark asphalt mixture, considering its global warming potential (GWP), production costs, reclaimed asphalt pavement (RAP) content in design, and its performance characteristics in an asphalt pavement with respect to thermal cracking, rutting and alligator cracking. As a result, the research’s outcomes would serve as a guideline to identify tolerance margins as well as ways to reduce environmental impacts without sacrificing the performance. The process is illustrated in Figure 8.

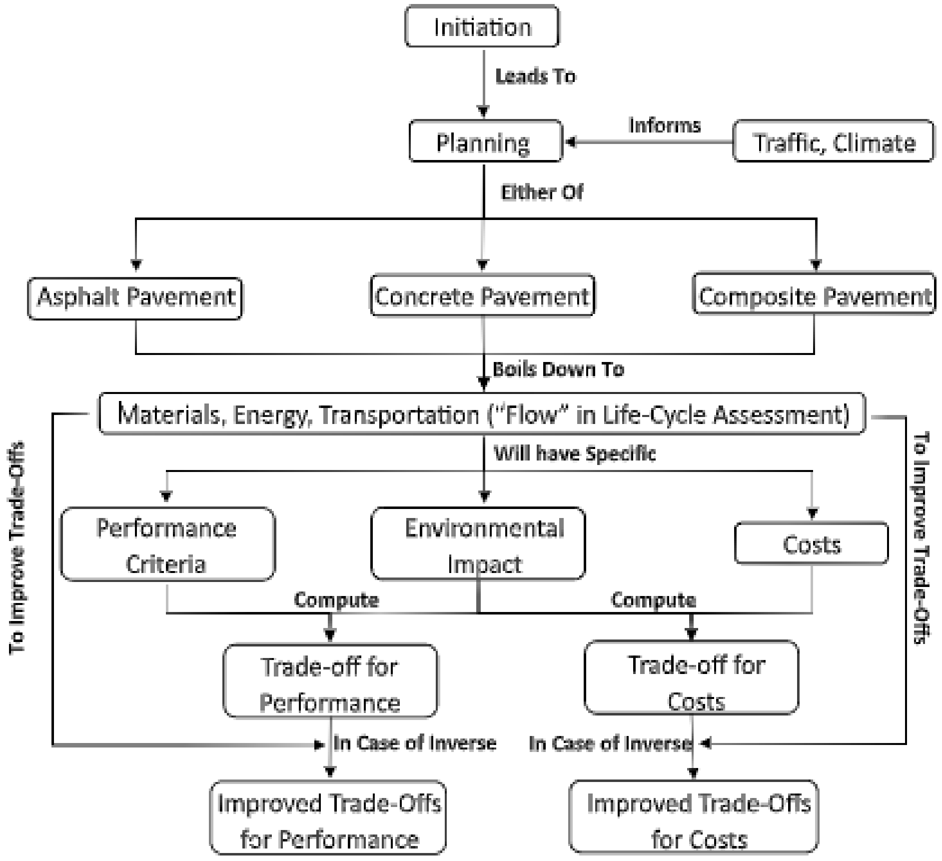
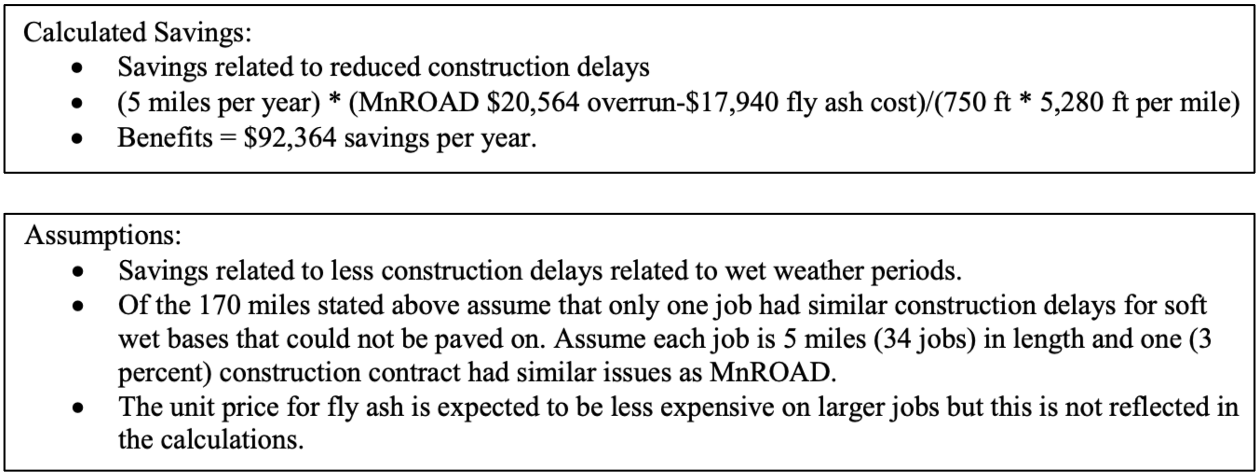


Figure 8: Life Cycle Informed Approach Process

Source: Bhat, "Life Cycle Thinking-Informed Approach to Support Pavement Design Decision Making", 2020

Another MnDOT research project benefit identified in Benefits of MnROAD Phase-II Research [Worel et al. Appendix D] included a "Field Investigation of Highway Based Material Stabilized with High Carbon Fly Ash". The investigation was conducted to evaluate the properties of high carbon fly ash stabilized highway base materials. However, the constructability benefits of fly ash served as a platform to quantify the cost savings due to reduced construction delays as fly ash helped to stabilize the construction platform for asphalt paving operations. This was proved especially helpful as well since the stabilizing agent maintained the platform even under wet weather where moisture could complicate the surface materials placement. The calculations are shown in Figure 9.



Calculated Savings:

- Savings related to reduced construction delays
- (5 miles per year) * (MnROAD $20,564 overrun-$17,940 fly ash cost)/(750 ft * 5,280 ft per mile)
- Benefits = $92,364 savings per year.

Assumptions:

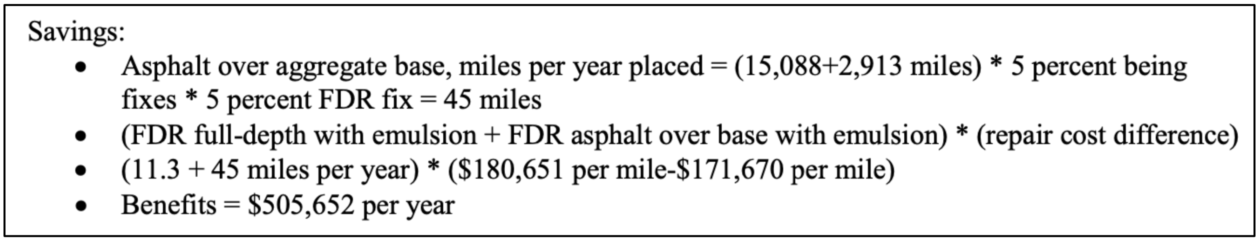
- Savings related to less construction delays related to wet weather periods.
- Of the 170 miles stated above assume that only one job had similar construction delays for soft wet bases that could not be paved on. Assume each job is 5 miles (34 jobs) in length and one (3 percent) construction contract had similar issues as MnROAD.
- The unit price for fly ash is expected to be less expensive on larger jobs but this is not reflected in the calculations.

Figure 9: Savings Calculations from Reduced Constructions Related to Wet Weather Periods

Source: Worel, “Benefits of MnROAD Phase-II Research”, 2015

This approach includes both construction cost savings and delays to the public. It was an annual estimate of benefits.

The research results of “Full-Depth Reclamation Stabilized with Engineered Emulsion” were included in the Benefits of MnROAD Phase-II Research [Worel et al. Appendix D] also. The motivation behind the investigation was to evaluate the characteristics and performance of existing hot mix asphalt (HMA) through full depth reclamation (FDR) with asphalt emulsion stabilization. The findings of the research were also used as a tool to design cost-effective design procedures that improve pavement’s strength and flexibility. To justify the FDR rehabilitation instead of traditional thick mill and overlay, the research had presented example savings from the repair costs. The savings calculations are illustrated in Figure 10.



Savings:

- Asphalt over aggregate base, miles per year placed = (15,088+2,913 miles) * 5 percent being fixes * 5 percent FDR fix = 45 miles
- (FDR full-depth with emulsion + FDR asphalt over base with emulsion) * (repair cost difference)
- (11.3 + 45 miles per year) * ($180,651 per mile-$171,670 per mile)
- Benefits = $505,652 per year

Where:

45 miles = Asphalt over aggregate base, miles per year placed = (15,088+2,913 miles) * 5 percent being fixed * 5 percent FDR fix

15,088 lane miles = bituminous overlays of bituminous pavement

2,913 lane miles = bituminous over aggregate base

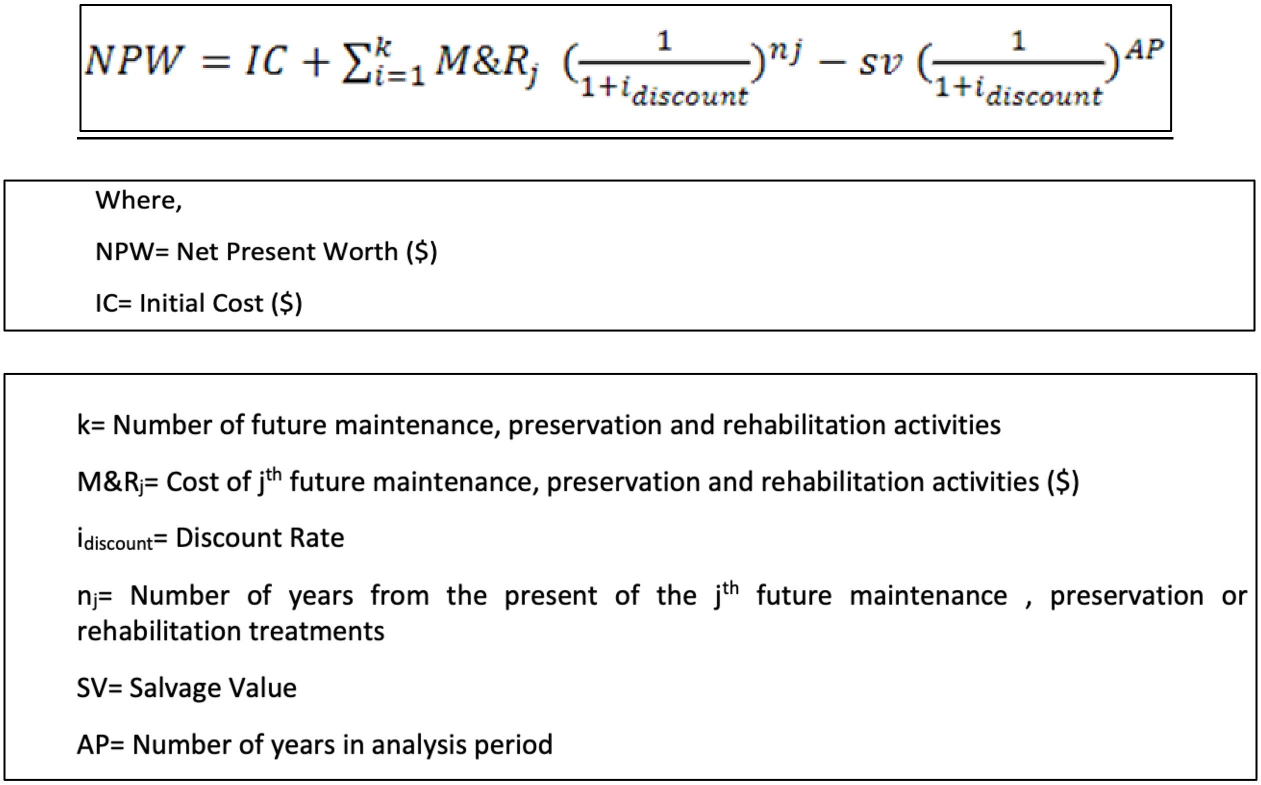
$ 180,651 = Cost of a thick mill and overlay from MnDOT pavement management system standard unit price

$ 171,670 = Cost of FDR and overlay from the Pavement Management System standard unit price

Figure 10: Savings Calculations for Full-Depth Reclamation Stabilized with Engineered Emulsion

Source: Worel, “Benefits of MnROAD Phase-II Research”, 2015

The research Investigating Life Cycle Cost Analysis to Identify a Sustainable Pavement Maintenance and Rehabilitation Strategy: A Case Study on Ontario Highways [Jannat et.al 2016] investigation looked into the net present worth (NPW) of the overlay alternatives to determine the life cycle cost of sustainable pavement maintenance and rehabilitation strategy. The NPW of the various alternative treatment options for deteriorating pavement were put into comparisons and the result showed that the resurfacing of pavement with dense friction course (DFC) and hot laid-1 (HL1) were the most cost-effective and this was demonstrated by the equation shown in Figure 11:



$$NPW = IC + \sum_{i=1}^{k} M\&R_j \; \left(\frac{1}{1+i_{discount}}\right)^{nj} - sv \; \left(\frac{1}{1+i_{discount}}\right)^{AP}$$

Where,

NPW= Net Present Worth ($)

IC= Initial Cost ($)

k= Number of future maintenance, preservation and rehabilitation activities

$M\&R_j$= Cost of j^{th} future maintenance, preservation and rehabilitation activities ($)

$i_{discount}$= Discount Rate

n_j= Number of years from the present of the j^{th} future maintenance , preservation or rehabilitation treatments

SV= Salvage Value

AP= Number of years in analysis period

Figure 11: Net Present Worth Calculations to Identify a Sustainable Pavement Maintenance and Rehabilitation Strategy

Source: Jannat et al., “Investigating Life Cycle Cost Analysis to Identify a Sustainable Pavement Maintenance and Rehabilitation Strategy: A Case Study on Ontario Highways”, 2016

The research had developed the strategy of comparing alternative treatment options through LCCA and simplified the maintenance and rehabilitation of pavement process. In addition to that, the mechanistic-empirical approach included in this research would further help to demonstrate the importance of implementing the design tool. The benefits were calculated on a NPW basis which considered the life cycle of the benefit including future maintenance and rehabilitation including the salvage value of the pavement.

3. Summary

The review of both highway systems and individual features research on quantifying benefits, if the research were implemented, revealed many approaches, and proposed methodologies. For highway systems approaches included:

- A broad approach used by MnDOT to evaluate an entire program devoted to highway research

- Considering user delay benefits because the public is the primary beneficiary of any system improvements by reducing travel times due to repairs of infrastructure

- Defining benefits in a very broad perspective by considering public policy impacts of improved highway systems and exploring methods that include public perception of the benefits including secondary economic and environmental benefits

When evaluating individual research project outcomes and their benefits, methodologies tended to consider direct economic benefits. The method included a variety of variables and factors, primary benefits included:

- Annual savings in maintenance costs

- More efficient designs for features that resulted in reduced capital costs

- Savings resulting from an extended life cycle for a highway feature such as a pavement improvement

- Benefit/Cost ratios for improvements including quantified crash reductions

- Reductions in material costs to construct a feature

- Factoring in the service life of the research implementation as well as the present value based upon an assumed discount rate

Secondary benefits were identified as:

- Benefits of an event driven mitigation strategy based upon research results that includes user and environmental benefits

- Consideration of sustainability benefits for research outcomes such as recycled materials

- Reduced construction periods based upon improved techniques resulting from research results

All of these academic research methodologies provide insight into potential methods to be used for the IRISE projects.

II. DOT Polices and Guidance

AASHTO (American Association of State Highway Transportation Officials) and transportation agencies provide national and state guidance on how to quantify the benefits of improvements to highway infrastructure through their publications. These publications may provide guidance on methods to determine research benefits.

Department of Transportation (DOT) on both the federal and state level are responsible for public policies for constructing and maintaining highway systems. Because funding has become more limited in past decades the need for building and maintaining these systems for more durability and sustainability is more important than ever. State DOTs are trying to innovate to extend the life of these systems and individual components. Because of this need, they may provide guidance on how innovation should be incorporated and quantified into the design, construction and maintenance process. DOTs also fund research to help create innovative solutions to durability problems so review of their guidance is very relevant.

It was important to consider how DOTs determine benefits in order to identify potential methodologies to quantify research benefits. This type of guidance can be provided on a federal or state level. The United States Department of Transportation (USDOT) and Federal Highway Administration (FHWA) policies and guidance were both reviewed for identification of such methods on a federal level.

In addition, the Pennsylvania Department of Transportation (PennDOT) publications were also considered for guidance because PennDOT is an IRISE partner and innovations could provide direct benefit to that agency. Because public-private partnerships are being used by many DOTs to implement innovation solutions, consideration was also given to the Pennsylvania Transportation P3 Office projects that were reviewed for innovative technologies and methodologies.

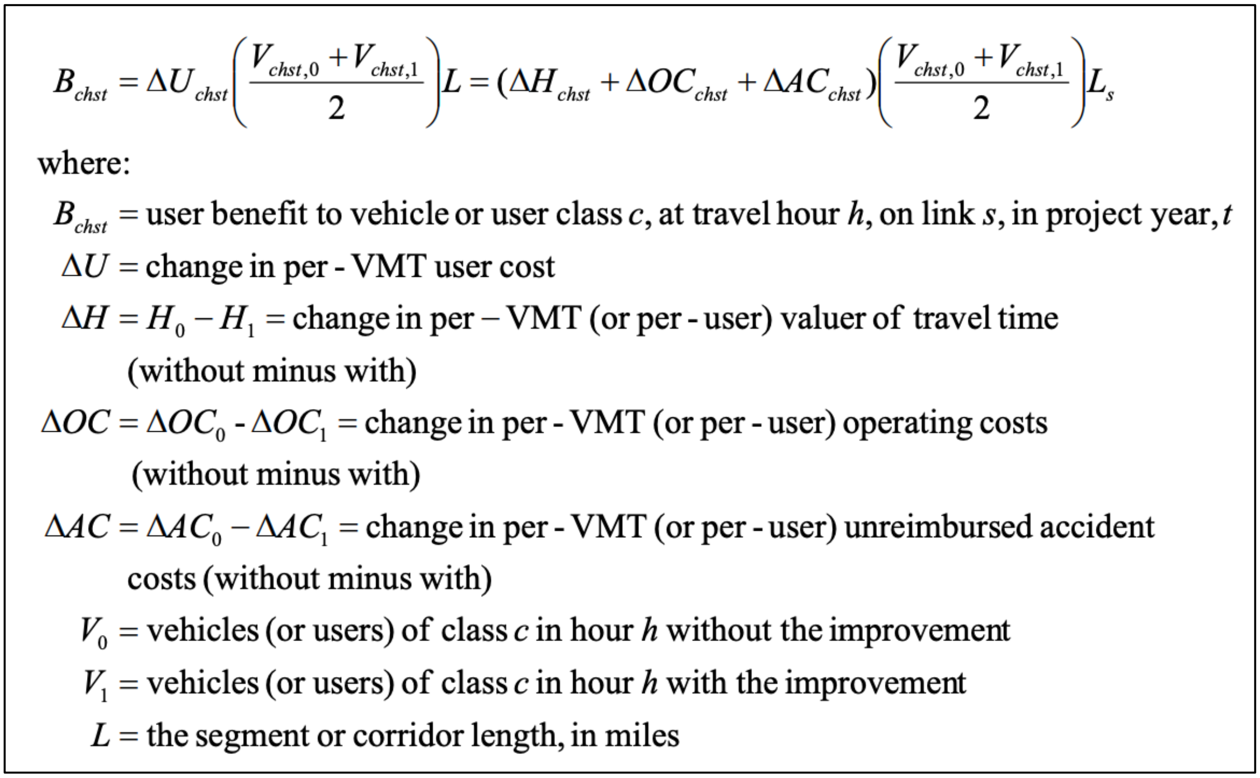
Similar to the review of academic research this scan was conducted with the goal of considering both system and individual component methodologies with an emphasis on pavement and landslide research innovations.

1. American Association of State Transportation Officials

AASHTO is considered to be national leader in creating tools for DOTs to design and maintain their highway systems. For this reason, publications were reviewed for methodologies. Two publications were identified as being relevant.

User and Non-User Benefit Analysis for Highways, 3rd Edition 2010 [AASHTO 2010] states that transportation improvements directly impact users as beneficiaries and indirect benefits for non-users. The user benefit methodologies, that the publication provides, are based on the three distinctive travel costs as they help to determine user benefits of a project. These include safety benefits, travel time monetized, operating costs monetized and a resulting benefit/cost method to compare these benefits to construction costs.

The manual provides a detailed guideline to calculate user benefits and Figure 12 illustrates is an example calculation for how vehicles benefit from a change to a highway system.



$$B_{chst} = \Delta U_{chst}\left(\frac{V_{chst,0}+V_{chst,1}}{2}\right)L = (\Delta H_{chst} + \Delta OC_{chst} + \Delta AC_{chst})\left(\frac{V_{chst,0}+V_{chst,1}}{2}\right)L_s$$

where:

B_{chst} = user benefit to vehicle or user class c, at travel hour h, on link s, in project year, t

ΔU = change in per - VMT user cost

$\Delta H = H_0 - H_1$ = change in per – VMT (or per - user) valuer of travel time (without minus with)

$\Delta OC = \Delta OC_0 - \Delta OC_1$ = change in per - VMT (or per - user) operating costs (without minus with)

$\Delta AC = \Delta AC_0 - \Delta AC_1$ = change in per - VMT (or per - user) unreimbursed accident costs (without minus with)

V_0 = vehicles (or users) of class c in hour h without the improvement

V_1 = vehicles (or users) of class c in hour h with the improvement

L = the segment or corridor length, in miles

Figure 12: The User Benefit Formula for Highway System Systems

Source: American Association of State Highway and Transportation, “User and Non-User Benefit Analysis for Highways”, 2010

Crash costs reductions, which are also a benefit, are a function of the speed, density of traffic, and the geometric design of the facility [AASHTO, 2010]. The savings in the crash costs and resulting safety benefits is the main goal of highway safety type improvements. The facility-specific crash and traffic volume data is be required in order to generate the without and with-improvement crash rates. The National Highway Traffic Safety Administration is an available resource for aggregated crash rate information.

The value of travel time identifies how the changes to the public can be quantified and how to put the time value in the highway benefit analysis. To quantify the effect as a result of a project on the user costs, the operating costs of vehicles which includes fuel and oil, maintenance, and tires must also be identified. The change in per-unit operating costs is crucial in order to carry out the user benefit formula. As previously discussed, the user costs are heavily dependent on the safety improvements as safety components targets to reduce the crash costs. The User Benefit Formula has two elements for the crash costs: crash frequency and crash unit costs.

Maintenance projects also affect the service life and consequently contributes to the user benefits by reducing the user cost and extending the project life. Even though the manual focuses mainly on capital projects, the same framework can be applied to evaluate the user benefits of maintenance projects.

The two costs that are important to evaluate the benefits as compared to the costs are the construction costs and the user costs. Once these costs are identified, the benefit cost analysis is performed to determine the feasibility of a project and a corresponding benefit/cost ratio.

AASHTO's Transportation Asset Management Guide 2002 [AASHTO, 2002] is another tool and was developed to assist in applying the various principles, techniques and tools to advance management in physical transportation infrastructure for highway agencies. This guide also provides information that could be applied to research innovations. The guide has listed the possible benefits resulting from asset management practices:

- Lower long-term costs for infrastructure preservation
- Improved performance and service to customers
- Improved cost-effectiveness and use of available resources
- A focus on performance and outcomes
- Improved credibility and accountability for decisions

The guide provides an interesting description of life-cycle management analysis including emphasizing the importance of customizing asset management improvement according to one's need. The basis of life-cycle management is the calculation of the value of the assets over its lifetime. This type of analysis is similar to how a research innovation's value might be determined, if the asset were to be improved in one part of the cycle as shown in Figure 13.

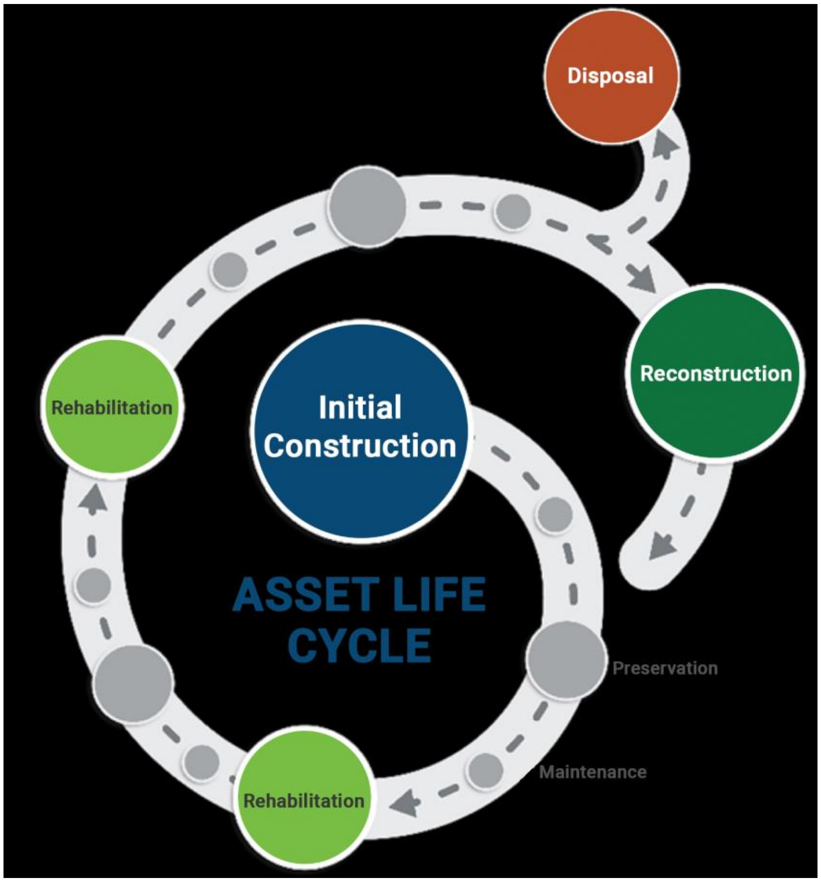


Figure 13: Asset Life Management Life Cycle

Source: Federal Highway Administration, "The Life Cycle Cost Analysis Primer", 2002

As shown asset life cycle analysis could introduce innovations and measure benefit in any of these stages including initial construction, rehabilitation and reconstruction.

2. United States Department of Transportation

The evaluation of benefits for particular actions on a highway system are typically done by DOTs when evaluating alternative solutions to specific issue. An example would be rehabilitation versus replacement of highway components. These evaluations may also compare user benefits of one alternative as compared to another. DOTs have used benefit-cost analysis methods to assist in these decisions for many years. These guidance documents were reviewed for applicability to this research.

The Life Cycle Cost Analysis Primer [FHWA 2002] publication from the Federal Highway Administration's Office of Asset Management details the procedures to perform Life-Cycle Cost Analysis (LCCA) while presenting the challenges of the total cost comparison of design or preservation alternatives.

The LCCA process steps demonstrated in the publication is summarized as the following:

1. Establish Design Alternatives

   Alternative A: Fewer construction and rehabilitation activities but more costly, less frequent but longer work zones to maintain level of service

   Alternative B: Less extensive and cheaper construction activities but higher frequency, more frequent but shorter work zones

2. Determine Activity Timing

	Activities	
Year	Alternatives A	Alternatives B
0	Initial Construction	Initial Construction
12		Rehabilitation 1 (8-year service life)
20	Rehabilitation 1 (20-year service life)	Rehabilitation 2 (8-year service life)
28		Rehabilitation 3 (8-year service life)
35	End of analysis period – residual service life if applicable	

3. Estimate Agency and User Costs

	Alternatives A		Alternatives B	
Year	Agency Costs	User Costs	Agency Costs	User Costs
0	$ 26M	$ 11M	$ 20M	$ 8M
12			$ 6M	$ 10M
20	$ 15M	$ 20M	$ 6M	$ 16M
28			$ 6M	$ 28M
35	$ (3.75 M)	$ (7.5 M)	$ (750,000)	$ (3.5 M)

Notes:
*M = Million
*Agency and user costs are in constant, base year dollars
*User costs = vehicle operation costs and traveler delay due to work zone activities, increases when traffic increases over time for similar work
*Costs for year 35 reflect the value of remaining service life for each alternative in year 35

4. Compute Life-Cycle Costs

		Alternatives A		Alternatives B	
Year	Discount Factor	Discounted Agency Costs	Discounted User Costs	Discounted Agency Costs	Discounted Agency Costs
0	1	$ 26M	$ 11M	$ 20M	$ 8M
12	0.6246			$ 3.75M	$ 6.25M
20	0.4564	$ 6.85M	$ 13.69M	$ 2.74M	$ 7.30M
28	0.3335			$ 2M	$ 9.34M
35	0.2534	$ (950,308)	$ (1.9M)	$ (190,062)	$ (886,954)
Total Costs (PV)		$ 31.9M	$ 22.79M	$ 28.3M	$ 30M

Notes:
*M = Million
*Discount factor = 4% for the present value (PV) calculation
*Inflation and discounts are applied

5. Analyze the Results

The results showed that Alternative A is the least total cost option. However, if the decision maker insists on applying Alternatives B due to its low initial construction and total agency cost, more analysis such as sensitivity analysis or probabilistic analysis could be done in order to justify the decision and see if it’s worth the investment.

In addition to this method, the primer also helps to understand the difference between a LCCA and a benefit-cost analysis (BCA). LCCA essentially serves as a tool that strictly compares the cost of the alternatives whereas BCA is useful when design alternatives do not yield equal benefits. The aforementioned LCCA example demonstrated was straightforward but various issues were often encountered when performing the LCCA and this included agency data requirements, uncertainty in both the inputs and outputs values as well as the user costs. This process could be used with informed data sources.

The FHWA report, Towards Sustainable Pavement Systems: A Reference Document [FHWA 2015], promoted the consideration of sustainability into the design and construction of pavements. It covered various topics that focused on sustainability which includes the methodologies to address the issues associated. However, for the purpose of this research, the focus is on how the sustainability can be quantified and measured. The reference document identifies which were the major sustainability impacts of a pavement and studied how each of them affect the environment positively and negatively.

The sustainability factors considered include:

- Energy consumption
- Habitat loss, fragmentation, and change
- Hydrologic cycle changes
- Air quality
- Mobility
- Access Freight
- Community
- Depletion of non-renewable resources
- Economic development

The document discusses pavement life cycle as it was crucial to understanding the sustainability effects of pavements. Sustainability was further divided into several aspects, and it included materials production, pavement design, construction, use, maintenance and preservation as well as end-of-life.

Last but not least, sustainability measurement is presented, and the four measurement tools were performance assessment, Life-Cycle Cost Analysis (LCCA), Life-Cycle Analysis (LCA) and sustainability rating systems. These tools could be used alone or in conjunction with one another to quantify the various aspects of sustainability. However, it's worthy to note that the report states "the sustainability measurement systems used depend upon the priorities and limitations of the agency and the characteristics of the project, as well as the desired outcomes viewed within the context of larger systems."

Even though the document did not quantify the benefits of the sustainable practice, the measurement system demonstrated could be used as a supplementary tool to quantify the monetary benefits from the practice of it. If the savings could be identified such as the reduced frequency of replacements for pavements, the LCCA procedures from the previously discussed materials "Life Cycle Cost Analysis Primer FHWA 2002" can be a useful tool.

3. Pennsylvania Department of Transportation

State DOTs such as PennDOT are responsible for the complete life of a highway system from initial construction to replacement/rehabilitation and extending the life cycle through maintenance. PennDOT publications were reviewed for guidance on projecting the future value of specific actions. Relevant manuals and policies were considered for methodologies that could be applicable to this literature review.

PennDOT Publication 242 Pavement Policy Manual May 2015 Edition [PennDOT, 2015] provides guidance on how to consider the longevity of pavements for policy considerations. While it does not discuss benefits of innovative pavement treatments specifically, it does provide guidance on determining the life cycle costs of alternative pavement options.

The policy manual has a provision for life cycle cost analysis guidelines in order to determine the most cost-effective pavement structure over a certain analysis period. The assumption made in the analysis considers each pavement type alternative to have an equivalent level of service and performance over the same analysis period. The most current LCCA Excel spreadsheet used was obtained from the PennDOT's Engineering and Construction Management System (ECMS) File Cabinet. The analysis procedures were reviewed, the analysis is based upon the following methodology:

The total present worth (PW) costs = Initial Construction + Maintenance Activities + User Delay

This is a great tool to quantify monetary benefits for every pavement projects. This method of analysis is similar to other referenced research findings on the value of research results because it considers all factors in the value of an outcome including construction costs, maintenance costs and user delays.

4. Pennsylvania Public-Private Partnerships

The PennDOT P3 office was established to seek alternatives to traditional design, bid, build, maintain and funding processes used by PennDOT. The goal was to find innovation methods that solve difficult problems. The office has conducted two projects to date that were reviewed for innovations and potential methods to quantify those innovation benefits.

The PennDOT publication, Rapid Bridge Replacement Program Lessons Learned Report [PennDOT 2019] was reviewed to determine how innovation was considered in the implementation of this unique bridge replacement program. A goal of the program was to accelerate the process of implementation of the bridge replacements by making the Development Entity (DE) responsible for design, construction, and maintenance of the structures. This responsibility could lead to the use of innovative practices in all three areas and thus accelerate construction timeframes and reduce costs.

A review of the report and discussions with the PennDOT P3 office identified several innovations developed during the program, these included:

- Installation of polyester polymer concrete overlays on all bridge decks to reduce long-term repair costs
- Use of pre-engineered designs for quicker construction time
- Innovative girder designs to reduce weight of structural components

Based upon discussions with the P3 office these innovations lead to reduced costs and construction time however the quantification of these benefits was not measured.

Compressed Natural Gas Fueling Stations Project is another project currently under development by PennDOT. This project which began in 2016 has the goal to design, build, finance, operate, and maintain compressed natural gas (CNG) fueling stations for public transit vehicle fueling in Pennsylvania.

Based upon discussions with the PennDOT P3 office many of the stations are now operating and the remainder in design and construction. Innovations and resulting benefits related to these CNG stations might include reduced fuel consumption, due to station locations and reduced emissions when compared to diesel bus operations. There is no methodology in place at this time to quantify these benefits

III.Categorization of Research Benefits

As the literature review has revealed the benefits of implementing research findings on a highway system or component can be measured by a variety of methods. These methods can generally be categorized as direct, such as economic benefits, and indirect such as user and sustainability benefits. Once the applicable type of benefit is selected the findings must be scaled up to project impact to a highway system.

1. Economic Benefits

The economic benefits of research innovations are the most immediately recognizable type of benefit from the perspective of a public agency that sponsors the research. Reducing construction, or capital costs, is an immediately realized benefit when an innovative highway feature is implemented. Work by MnDOT [Worel et al. 2015], [Bhat et el. 2020], [Coleri et el. 2018] and [Jannat et.al 2016] all identified how these benefits can be monetized. Economic benefits can also be realized over time by reducing:

- Reduced construction costs
- Frequency and cost of future routine maintenance and repair costs
- Major repair costs in the future
- Extended life cycle periods for complete replacement or major repairs

The value of these economic benefits can be calculated using engineering economic analysis tools that consider the present value of these present and future benefits.

Highway agencies have also recognized the value of these types of analysis in alternatives evaluation methods as identified in The Life Cycle Cost Analysis Primer [FHWA 2002] and PennDOT Publication 242 Pavement Policy Manual May 2015 Edition [PennDOT, 2015]. A challenge in determining life cycle benefits is determining an accurate estimate of the future reduced costs for repairs and the extended service life of components.

It is noted that some research results may require increased capital costs that will offset future maintenance costs or extend service lives. This type of analysis of benefit can also be determined. Reduced construction time, using an innovative construction method, is also an immediate economic benefit that could be measured based upon material and labor costs during the construction process.

2. User Benefits

User benefits analysis provide a method to evaluate outcomes beyond the direct economic impacts of a research innovation. For example, [Dolama et al. 2020] quantified secondary user benefits that related to one-time event mitigations such as landslides. These benefits included traffic delays on detour routes. [Winter et el. 2012] also went beyond direct economic benefits and quantifies benefits to the public by minimizing disruptions to the highway system.

While user benefits maybe more difficult to directly project they represent a quantifiable benefit to research findings that involves minimizing disruptions to the traveling public and secondary economic impacts to commerce such as local business disruptions.

3. Sustainability Benefits

Evaluating the sustainability of highway features is an emerging field of research and quantification of those benefits, due to research findings, is important. Research findings that provide more sustainable materials and construction methods are two examples of sustainability benefits that could be identified.

[Guinta 2017] The FHWA report “Towards Sustainable Pavement Systems: A Reference Document” [FHWA 2015] goes beyond direct economic benefits and provides a framework for determining sustainability benefits for pavements for items such as energy consumption and non-renewable resources.

As the field of sustainability becomes a larger component of decision making in highway systems these benefits will be important to be quantified.

4. Scale of Benefits

When evaluating the benefits of a specific research recommendation the impact of the benefit must be applied to a geographic scale to determine the global benefit. The geographic impact area of the innovation may include national, state or local benefits based upon the data available to quantify the scale and potential area of influence. As much of the literature review revealed and as an example, data on pavement costs related to initial construction, repairs and replacement must all be available to calculate the maximum benefits.

Any scaling up of benefits will be contingent upon available data on not only for capital costs but repair and future life cycle periods to provide the most accurate estimate possible. The databases maintained by highway agencies that tracks these types of costs, will be critical to accurately estimating these benefits.

An alternative to scaling up benefits would be to apply findings to a particular case study such as a project or corridor where more detailed data might be available to estimate benefits.

IV. Summary

The literature review of current research, policies, and procedures to quantify research benefits to highway systems and components revealed useful methodologies. These methods can provide a framework for considering the benefits of these six specific IRISE research projects:

- Landslide Best Practices
- Material Compatibility Repair
- Joint Design Optimization
- Preliminary Evaluation of Pavement Surface Distresses Related to Pavement Marking
- Remote-Controlled Technology Assessment for Safer Pavement Construction and QA/QC.
- Development of Simplified Mechanistic-Empirical Design Tool for Pennsylvania Rigid Pavement

While each of these projects will produce unique benefits many of the benefits can be quantified based upon direct and indirect impacts. Impact areas to be considered for each project will include:

- Direct Economic Benefits
- Highway User Secondary Impacts
- Sustainability Considerations
- Scale of Research Impacts

Development of Methodologies

The first task included a selection of current or past practices related to the benefits of implementing research findings. The findings of that task identified potential methods and type of benefits that could be applied to the Task for methods that were developed.

Based upon the results of the literature review, methodologies were initially developed for each of the six research projects with the goal of quantifying the benefits of the research results. These methodologies used varying approaches to demonstrate how different types of research projects can result in benefits to the highway system.

Two basic types of benefits can result from this type of research. These benefits include user benefits, which are delay and safety to public users of the highway system and reduced cost benefits. Reduced cost benefits may include capital costs such as design and construction costs or annual costs such as maintenance. The goal of this task was to select methodologies for each project that will determine which of these three types of benefits are relevant and how these methods will be applied to the five research projects. Also included in this task is a plan to collect and establish baseline data for comparison to the benefits if the research results were implemented for a particular highway feature.

I. Options for Categorization of Research Benefits

A review of the literature search revealed benefits can be categorized in several ways including economic, user, sustainability, and scale. The literature review, as well as discussions with each of the principal investigators for each project, were used to select which options best fit each project to measure benefits. The following is a summary of the benefit type options considered.

1. Economic Benefits

Economic benefits are an immediate or long-term result of implementation for some research project types. Long term economic benefits may not be realized until the service life of a highway component is extended. These future benefits may be reduced maintenance or replacement costs. Capital costs could be higher for some innovations which would then result in long term benefits. All of these types of economic benefits were considered when selecting a methodology for a specific project if cost benefits are anticipated to be a result.

2. User Benefits

User benefits may only apply to project types that directly impact the traveling public or economic activity of land uses adjacent to the highway. Projects that shorten construction periods and result in less delay would have a direct user benefit. Secondary benefits such as land use impacts maybe more difficult to measure but could be relevant if a highway is closed indefinitely or during a construction period. These types of benefits could be measured for a specific type of research result for a project.

3. Sustainability Benefits

Sustainability benefits are difficult to measure for some types of highway components that are improved by research results. The materials and processes used to construct highway improvements can be made more sustainable but limited research has been done in this area.

4. Scale of Benefits

The benefits of a specific research recommendation must be applied to a geographic scale to determine the global benefit. This will be dependent upon available data and impact expectation of the innovation. Another option is to evaluate specific projects as case studies and estimate the benefit which could be scaled up to a larger area.

II. Categorization Methods

A process was developed to review each project and categorize which benefits would be relevant. This method considered all of the aforementioned types of benefits and concluded with a recommended methodology.

The following describes how each of the five projects were categorized and the logic for how the screening process was developed and applied. Each project was reviewed in terms of the type of highway benefits generally expected and the process was applied.

1. Project Types

Because the five projects are being studied in detail, the researchers investigated the primary benefits each project focuses on. In general, the projects were categorized into several groups based on its primary type of benefit. This included the highway feature innovation, capital cost changes, maintenance cost impacts and life cycle improvements. Nevertheless, it was found that these projects potentially share mutual benefits of interest including economic, user and sustainability.

2. Screening Process

The process was developed to determine how these projects impact the benefits differently. Economic benefit was first studied, as this relates to construction and maintenance costs, present value of innovation, net present value of life cycle and benefit/cost ratio. User benefits on the other hand impacts the traffic users as well as the commerce flow. Last but not least, sustainability benefits would be determined by analyzing the project energy consumption, use of non-renewable resources and how it affects the air quality as well as the noise levels of the surroundings.

3. Application of Process

Once the benefits are determined, the scale of the benefits needed to be identified. This was done by checking if the data needed for the project benefit analysis could be found nation-wide, state-wide, or unique to a particular project. Nation-wide data might be available from the Federal Highway Agency, State-wide data could be retrieved from PennDOT through the Engineering and Construction Management System (ECMS) [Pennsylvania Department of Transportation n.d.] and last but not least, unique benefits could be based on case studies for particular highway improvement programs or projects.

Figure 14 illustrates the process described that was applied to each project. This process provides a consistent examination of potential benefits in order to create a unique methodology for each of the six projects

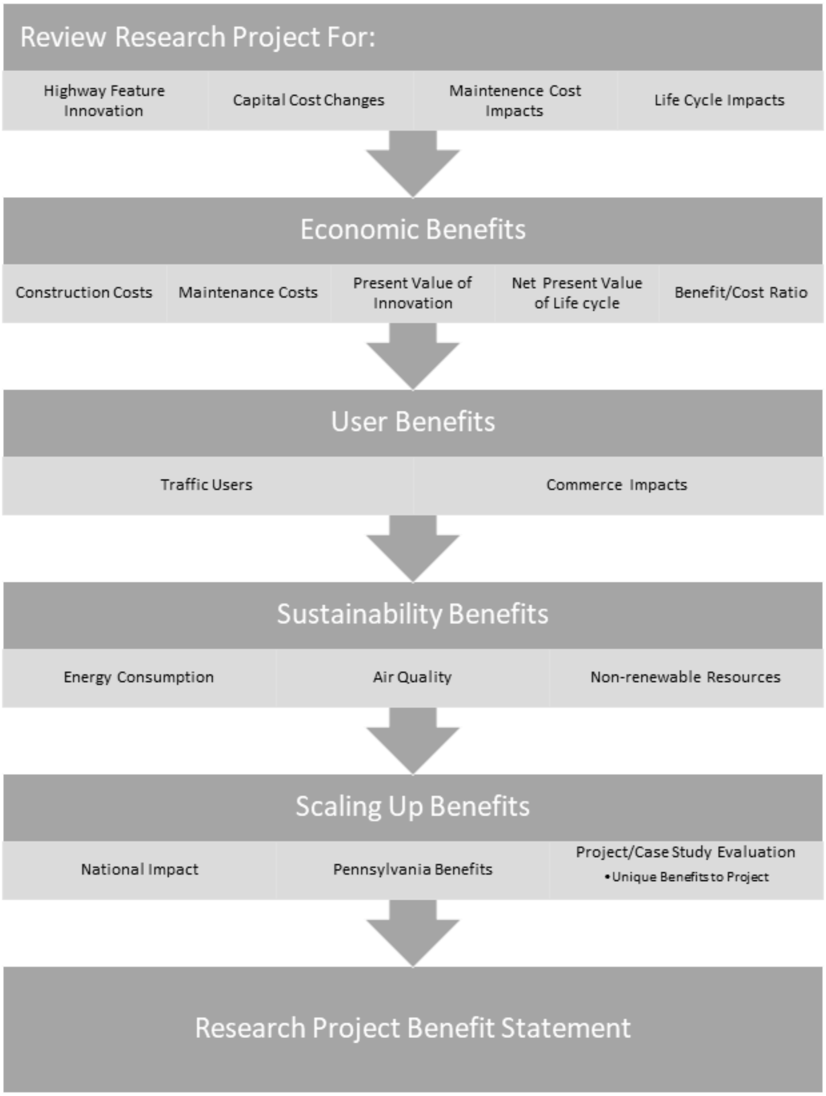


Figure 14: Methodology Process Chart

III. Recommended Methodologies

On the basis of the screening process developed as illustrated in Figure 14, a detailed methodology was developed for each project. This provides a description of the process for each project. Initial screening forms were developed to refine the process for each of the six projects. Baseline data was obtained and used to establish baseline information. The final task expanded upon the initial baseline data collected to determine the best available information for the analysis. Once this information was obtained it was altered for the final methodology described in this report.

Summary of Research Results

Methodologies were developed for each of the five research projects with the goal of quantifying the benefits of the research results. These methodologies use varying approaches to demonstrate how different types of research projects can result in benefits to the highway system.

After development of the methodologies data was collected for the analysis of the benefits. This work included evaluating available information and determining the current cost of user conditions followed by projected results with the research findings implemented on either a case or universal basis. The following summarizes the methodology, baseline data and research benefits results for each project.

I. Early Opening to Concrete Pavements to Traffic

Earlier opening of concrete pavement to traffic without an impact to short- and long-term pavement performance can reduce construction time and improve driver satisfaction by opening roadways in a shorter period. Improving concrete strength estimations in the field, strength gain predictions and early age damage modeling are key to optimizing early opening to traffic. To evaluate the estimation of concrete strength, laboratory and field studies were conducted using maturity and ultrasonic tomography. It was found that both methods were efficient and resulted in reasonable concrete strength estimations for in-situ pavement, but ultrasonic tomography was found to have advantages over the maturity method, such as improved correlation and mobility. A web-based tool was created to facilitate the implementation of this procedure for determining the optimal time when paving projects can be opened to traffic without significant damage [Khazanovich, 2021].

A user cost analysis in the research study showed that early opening pavement to traffic would have significant benefits on urban arterial roadways. An analysis of a hypothetical construction project involving an urban street closure was performed to demonstrate the potential vehicular user benefits of opening it to traffic earlier than a typical construction project would permit.

Another benefit of this research finding is that High Early Strength (HES) concrete may not be required to meet a project schedule for opening the roadway to traffic. A recent construction project in PennDOT District 11-0 demonstrated that by using a standard mix design in lieu of HES combined with the in-situ testing and development of maturity curves HES concrete was not needed. Identifying the strength of the concrete more rapidly allowed construction to proceed without the use of HES concrete and without affecting the project schedule. The cost of HES concrete is higher than the standard mix while also less durable.

These two case studies were selected to demonstrate the benefits of the research results. These demonstrate the benefits to users of highways and construction costs.

1. Baseline Conditions

To demonstrate the benefits to users a baseline was established for traffic delays and construction costs. The baseline for the user benefits involved development of a traffic simulation model to compare traffic delays with and without street closure. The baseline for the construction project was project costs.

Urban Network Case Study

In order to demonstrate the benefit of opening a concrete pavement construction project earlier by use of the research results, a hypothetical case study, as detailed in Section 7 of the Early Opening Final Report [Khazanovich, 2021], modeled a subarea of Downtown Pittsburgh. This urban location was selected because it demonstrated how a critical location of a closed roadway in a complex street network disrupts traffic patterns and an early opening significantly benefits the traveling public. The location in the Pittsburgh central business district is shown in Figure 15.

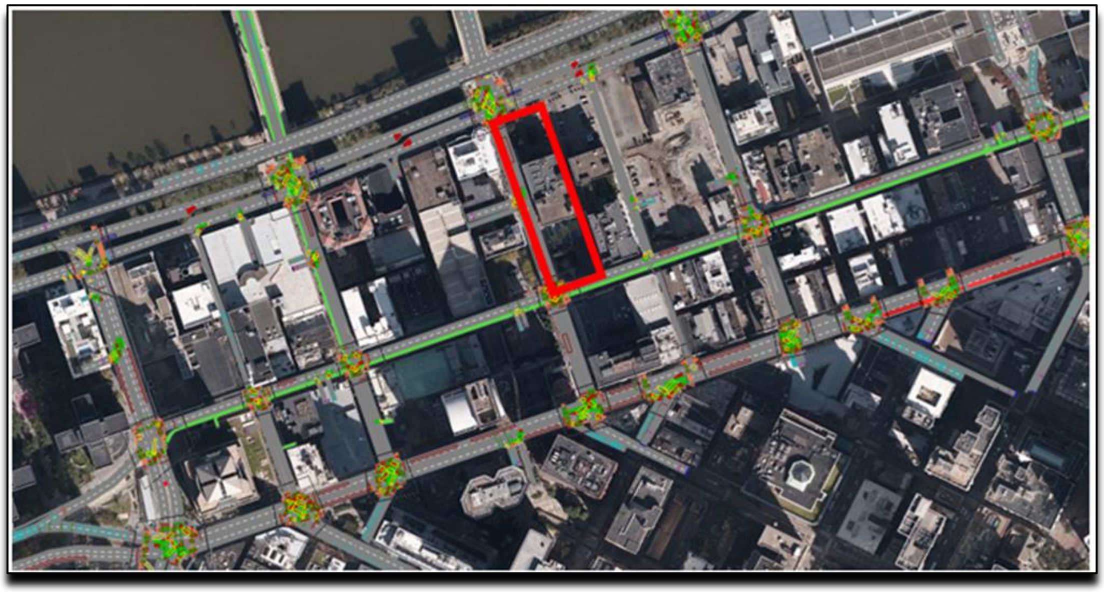


Figure 15: Downtown Pittsburgh VISSIM Model for PM peak hour

Source: Khazanovich, “Early Opening of Concrete Pavements to Traffic”, 2021

The traffic model was built as a microsimulation environment using the traffic simulation model software VISSIM. This was developed for the PM peak hour of traffic conditions under non construction operations. The methodology was subsequently developed to demonstrate the resulting work-zone impacts for the remaining hours of the day. The model was then used to estimate work zone travel delays.

The current method used by PennDOT to estimate work zone delays involves the Work Zone Delay Analysis Workbook [PennDOT], in tandem with evaluation software that can be calibrated and used to assess possible scenarios of work zone activities, to determine highway traffic flow efficiency under work zone conditions. The method using VISSIM, which is more complex and accurate in an urban environment, estimates congestion and transportation efficiency in arterial roadways during construction as compared to normal operating conditions.

The hypothetical case study assumes that ultrasonic tomography or maturity curves were used to reliably estimate concrete strength which would improve early opening strength predictions. The research results emphasize that the strength of the concrete must be higher than the stress imposed by the expected traffic load. Therefore, the VISSIM model used in the case study was an integral part of determining the benefits to roadway users to early opening of roadways in urban areas. The study focused on the benefits of one day of early opening of the street and the associated user benefits [Khazanovich, 2021].

Route 837 Construction Project Case Study

In the separate construction case study provided by Golden Triangle Construction, a portion of State Route 837 was originally bid to be constructed with high early strength (HES) concrete. The baseline was the costs in the contract to utilize HES concrete, which is more costly but anticipated to be needed to meet the construction schedule. The section of Route 837 that was reconstructed was in the West Homestead Borough of Allegheny County, beginning at the intersection of Route 837 and Neel Street and ending 1700 feet west of the intersection of Route 837 and 8th Avenue.

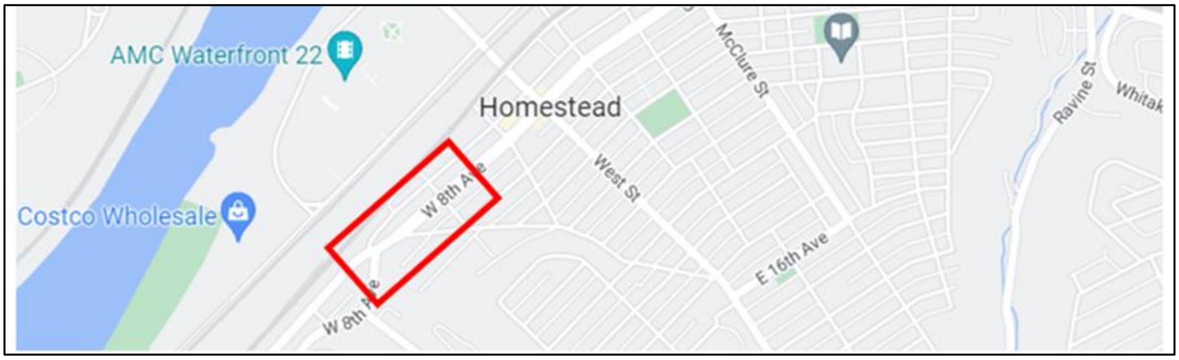


Figure 16: Route 837 Case Study Location

Source: Google Maps

The benefit was achieved by generating maturity curves in the field by utilizing maturity sensors in the test cylinders and water curing them to determine when the normal strength PennDOT class AAPAVE mix would achieve a compressive strength of 2000 psi. This occurred in 14-16 hours, rather than the typical 24 hours. The use of the maturity sensors in combination with the normal strength PennDOT class AAPAVE mix allowed for concrete to be placed on back-to-back shifts rather than missing a shift in between waiting for strength. This benefit allowed the highway to be opened to traffic on the same schedule without the use of the more costly HES concrete. The project quantity was 6,300 cubic yards of concrete pavement.

Methodologies Developed

For the user benefit hypothetical construction project in an urban street system, the work zone analysis tool, VISSIM, was used to simulate a potential work zone scenario for a segment of 7th Street, from Fort Duquesne to Penn Avenue, in Downtown Pittsburgh. A total of 23 alternate routes with the most significant volumes, due to the street closure, were chosen for analysis, and potential diversion routes were developed. The methodology was developed to utilize field travel times, as reported by Google, to understand differences in delays and travel times between the PM peak hour and other hours during the day. The final result of the analysis was the estimate of hours of user delay eliminated for every 24 hours of early opening of the roadway segment, which was then translated to user costs [Khazanovich, 2021].

The Route 837 case study project involved removing the existing concrete roadway and underlying subbase, completing new drainage work, placing a new 4” layer of 2a subbase, a new 4” layer of asphalt treated permeable base course then constructing 10” of new plain cement concrete roadway. The methodology was the comparison of the HES concrete cost, in the original construction project, with the normal strength PennDOT class AAPAVE mix and maturity sensors with the cylinders that reach the 2000 psi mark in 14-16 hours.

2. Benefit Analysis Results

Delay costs for the hypothetical urban arterial construction project used the assumptions that the 24-hour delay can be estimated based on information from a single PM peak hour by using delay coefficients, the diurnal volumes were distributed as PennDOT suggests in their Traffic Data Report (2019), and travel time from Google maps was used to calculate delay adjustment coefficients for different periods of the day. Table 1 represents the costs of delay caused by work-zone in Pittsburgh downtown network, broken down by vehicle type.

Table 1: Cost of Delay Caused by Work-Zone for Pittsburgh Downtown Network

Time of day	**f_d**	**f_v**	**f_s**	**Passenger Car Delay (h)**	**HGV Delay (h)**	**Bus Delay (h)**	**Total**
AM peak	0.91	0.95	1.5	287.6	1.9	2.0	291.5
Mid-day	0.97	0.90	3	581.7	4.1	4.1	589.8
PM peak	1.00	1.00	1	222.8	1.4	1.6	225.8
Evening	0.84	0.85	1.5	239.3	1.8	1.7	242.7
Free Flow hours	0.76	0.65	5	547.2	5.3	3.9	556.4
Total Delay (h)				1,878.5	14.4	13.2	1,902.2
User Delay ($)				$67,064.0	$377.0	$2,998.7	$70,439.7
Vehicle Operating Costs ($)				$49,217.9	$2,297.8	$1,689.7	$53,205.4
Total User Cost of Delay ($)				$116,281.9	$2,674.7	$4,688.4	$123,645.1

Source: Khazanovich, “Early Opening of Concrete Pavements to Traffic”, 2021

This user benefit analysis showed that street closures due to work-zones in Pittsburgh Downtown can save user delay costs of $123,645. By shortening the construction time in urban areas such as the portion of 7th Street that was simulated in this model, a significant amount of user delay cost can be saved.

The benefit of the Route 837 case study was the reduced costs to achieve the same construction schedule. The reduction in the cost of the specified concrete was quantified by comparing the normal strength PennDOT class AAPAVE mix to the HES mix. The unit cost differential on materials was $6.50 per cubic yard. This translates to a total cost benefit of $40,950 by using the normal strength PennDOT class AAPAVE mix in lieu of the HES mix. The additional benefit is the increased durability utilizing the superior material.

II. Preliminary Evaluation of Pavement Surface Distresses Related to Pavement Marking

This research project studied pavement sections along the longitudinal joints exhibiting distresses and identified the cause of the problem to determine if it arises from the pavement markings. It was determined that the pavement markings do not deteriorate the longitudinal joints, however other factors that impact the joint result in a repair process that requires removal and reinstallation of the markings. The project determined an appropriate mitigation strategy that extends the life of the longitudinal joints and preserves the life of the markings [Khazanovich, 2022].

One of the benefits of this research was the expected extended life of the longitudinal pavement markings, that will not be required to be replaced when the joints are repaired. In order to quantify the benefits of the extended life of the pavement markings several case studies were evaluated that involved extensive longitudinal joint replacements and what the corresponding costs that involved replacement of the thermoplastic pavement markings

1. Baseline Conditions

Development of the methodology and establishing baseline conditions involved evaluating two different case studies in PennDOT District 11-0, that were provided from PennDOT ECMS. These case studies focused on Allegheny, Lawrence, and Beaver County Interstate highways, which underwent recent asphalt major longitudinal joint repairs. These case studies were selected because they are high volume and high-speed roadways with significant longitudinal joint failures. Repair of these types of highways results in significant costs for both joint and markings repairs. Table 2 shows the locations along each interstate, that was part of the repair contracts, selected for the case studies.

Table 2: 2020-2021 Interstate Longitudinal Joint Repair/Rehabilitation Project Location PennDOT District 11-0 Repair Contracts

Project #	**County**	**State Route**	**Year**
114544	Allegheny	0079	2020
114544	Allegheny	0279	2020
114544	Allegheny	0376	2020
114544	Lawrence	0376	2020
114545	Lawrence	0376	2021
114545	Allegheny	0079	2021
114545	Allegheny	0376	2021
114545	Allegheny	0579	2021
114545	Beaver	0376	2021

Source: PennDOT ECMS

Construction plans for each case study were obtained from ECMS and used to determine the lineal feet of each longitudinal joint repair done for the respective projects. The longitudinal joint construction pay item selected from ECMS, was item 9000-9469 Liquid Asphalt Patching Material – Hot Pour Mastic.

This item quantity was used to determine lineal feet of the longitudinal joint repair area. It was determined that a total of 1,854,724 lineal feet of longitudinal joints were repaired at $1.60 per pound for the two projects. The length of the joint repairs was determined from the application rate of one pound of this material, which repairs 1.1765 lineal feet of the joint.

When joints are repaired, reapplied pavement markings are an additional cost to the repair. The total cost of joint repairs was determined to be $2,544,512. While this would be a significant benefit if the life of the joint was extended, this benefit analysis focused only on the pavement marking costs. The joint repair costs service life extension is another benefit but not quantified in this analysis.

The lineal feet of marking for each of the repair projects was determined from the item tabulations for each contract. There are two options for the application of pavement markings. Thermoplastic pavement markings are a unit cost of three dollars per lineal foot. Paint pavement markings are a unit cost of one dollar per lineal foot. This price difference can be attributed to the durability and quality of each pavement marking type.

For markings on highway volume and high-speed highways such as these referenced repair projects, thermoplastic markings are used due to their increased durability but have higher unit costs. Although paint pavement markings were included in the contracts, their cost was not included in the analysis of the case studies. Table 3 shows the breakdown for thermoplastic pavement marking types per project and their respective lengths repaired in the case studies

Table 3: Thermoplastic Pavement Marking Types and Lengths

Project #	Type of Marking	Lineal Feet
114545	4” Yellow	113,629
114545	6” White	141,375
114545	8” White	16,583
114545	12” White	1951
114544	4” Yellow	16,472
114544	6” White	236,681

Source: PennDOT ECMS

The average cost per lineal foot was applied to the lineal feet for the total of the projects and then the potential savings for the thermoplastic pavement markings to be reapplied was determined. The total lineal feet of new pavement markings were found to be 526,671 which results in a total cost of $718,512. It is expected that with an increased service life of the longitudinal joints the reapplication of the markings would be less frequent, and the savings would result. The actual increase in service life of the joints and markings is not known at this time and further research would have to determine the extended service life.

2. Benefit Results

The methodology selected was to determine the savings in cost of reapplying thermoplastic pavement markings due to the needed repair from deterioration of the longitudinal joints. When joints are repaired the reapplied pavement markings are a cost that could be replaced less frequently if longer lasting joints were constructed.

Based on the case studies of recently repaired major highways in PennDOT District 11-0, the potential savings for reapplication of longitudinal pavement markings could be $1,937,772 for thermoplastic application for the two case studies evaluated. These savings could contribute to decreasing maintenance and replacement costs of the roadway longitudinal joints in addition to the pavement markings.

III. Remote-Controlled Technology Assessment for Safer Pavement Construction and QA/QC

The researchers conducted a broad technology scan to identify technologies that reduce worker danger during pavement testing and other high-risk activities adjacent to active traffic in work zones [Khazanovich, 2022]. The original scope of the project was to identify technologies related to paving operations but was broadened to all construction activities in an active work zone and identified 3 specific technologies of benefit.

Implementation of technologies will improve the safety and efficiency of construction activities in this higher-risk work area. The primary benefit is fewer worker injuries in the higher danger sections of work zones due to vehicle intrusions. Crash and worker injury data related to vehicles entering the work zone and injuring highway construction workers that could be mitigated by remote-controlled technologies was identified. The goal was to quantify the number and value of workers' injuries or fatalities in a work zone that could be mitigated.

1. Baseline Conditions

In order to determine the potential benefits of reducing worker injuries due to vehicle crashes in active work zones through technologies, data was collected on current work zone crashes and the costs of those injuries that could be mitigated by these measures. A search of national and Pennsylvania data was conducted, and a baseline of crash and injury data was established so that the mitigation strategies could be tested against.

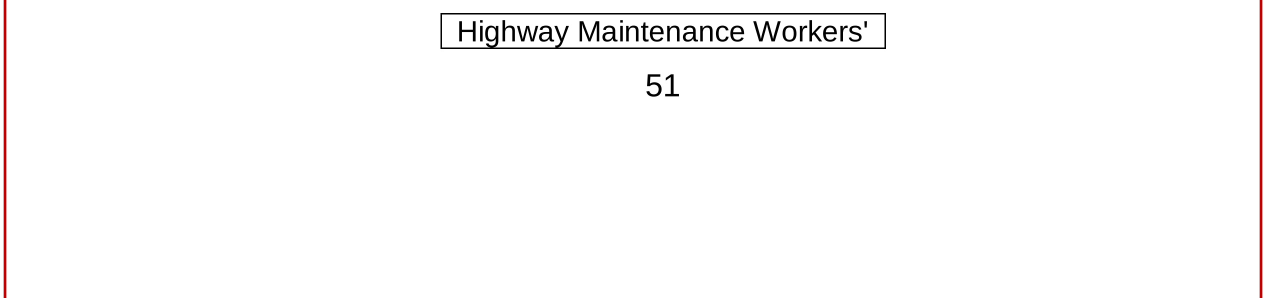
NIOSH and Other National Data

Working in highway areas is dangerous. According to the National Institute for Occupational Safety and Health website, highway maintenance workers and construction laborers were one of the occupations that accounted for 67 percent of all work-related deaths in work zones from 2003 to 2017(NIOSH, 2021). In fact, there were 142 reported highway maintenance related fatalities and 473 cases involving the deaths of construction workers in the span of 14 years.

The heavy/civil engineering construction and specialty trade contractors that work in the private sector accounted for 62 percent of workers' fatal injuries in highway work zones. On the other hand, 14 percent of highway work zones related fatal injuries were in the government sector consisting of both state and local government workers. Each state and local government workers account for about 7 percent of the deaths in road construction.

Another source of national data is the US Bureau of Labor Statistics which published a report titled “Fatal Occupational Injuries at Road Construction Sites, 2003 – 2018”. The report's data was broken down into various categories including both private and public sectors. Highway maintenance workers which are classified as Construction and Extraction Occupations totaled about 153 fatality cases. Table 4 summarizes the deaths reported for each year:

Table 4: Highway Worker Fatalities 2003-2018



Fatalities	
Year	Cases
2003	9
2004	9
2005	10
2006	10
2007	3
2008	8
2009	8
2010	Not available
2011	13
2012	23
2013	5
2014	7
2015	16
2016	8
2017	13
2018	11

Source: US Bureau of Labor Statistics

Crash Data in Work Zones

Working in active highway work zones where traffic can intrude into the work area is also very dangerous. The Fatality Assessment and Control Evaluation FACE program was created by the (CDC) and NIOSH in 1982 with the intent of providing the public with detailed fatality investigation reports. Participating states established agreements with NIOSH for conducting investigations of occupational fatalities associated with renewable energy, logging, agriculture, transportation, semi-truck and dump truck fatalities, public sector workers, multidisciplinary workers, and many more. As a result, State FACE programs were established where the targeting investigations of death slightly differ from the NIOSH FACE program.

For the purpose of this study, the researchers focused on cases that involved vehicles intruding into work zone areas from the State FACE reports. From the State FACE reports that had highway work zone as a targeted location; 28 fatalities were identified dated from 1992 to 2020 [Khazanovich, 2022]. Table 5 details the cause of each fatality for every incident reported.

Table 5: Fatalities Involved in Highway Work Zones 1992-2020

Publication Date	State	Title

9/24/1992	MN	Highway construction flagman dies after being struck by a pickup truck.
4/26/1994	MN	Highway construction worker dies after being struck while crossing roadway.
11/30/1999	NE	Member of road striping crew struck by semi.
5/23/2000	OK	A roller operator and a work crew foreman died when they were struck by a motorist in a highway work zone.
11/15/2000	CA	A highway worker dies when struck by a speeding vehicle while picking up cones on an interstate highway.
11/24/2000	CA	A construction flag person dies after being backed over by a truck.
2/3/2001	WI	Construction laborer killed when run over by dump truck in highway work zone
12/1/2001	IA	City street worker was struck and killed by a speeding car.
3/7/2002	NJ	Truck driver killed in highway work zone collision.
4/7/2003	MI	Highway worker killed by passenger vehicle while setting up highway work zone warning signal.
6/10/2003	CA	A construction worker jumps over a cement barrier onto an interstate highway transition road and is killed when struck by an oncoming vehicle.
8/17/2004	OK	Laborer died after being struck by a vehicle in a roadway work zone.
8/30/2004	NJ	Highway worker struck and killed by an auto while filling potholes.
8/30/2004	NJ	Municipal road worker struck by a truck at a worksite.
9/23/2004	NY	Flagger dies after being struck by a pickup truck in a highway work zone.
7/28/2005	CA	A construction laborer died when he was struck by a fast moving vehicle as he crossed the roadway in a street construction work zone.
7/29/2005	WA	Utility construction supervisor killed when struck by a pickup truck at a work zone in Washington State.
12/28/2005	NY	Three construction workers killed after being struck by a bus in a highway work zone.
1/31/2006	WA	Flagger fatally injured when struck by a car at a highway work

		zone in Washington State.
10/23/2006	WA	Maintenance worker killed when struck by a vehicle along a highway in Washington State.
6/13/2007	MI	Surveyor dies when struck by oncoming vehicle.
9/12/2007	MI	Worker dies as a result of being struck and pinned between two vehicles while repairing potholes.
12/28/2007	MA	A municipal worker struck by a motor vehicle while patching a pothole
8/26/2008	MI	Supervisor/foreman struck by a pickup truck while placing channelizer drum in road.
6/16/2010	MA	Municipal laborer dies after being struck by a motor vehicle while closing a water gate valve
5/14/2018	MA	Foreman of a highway line painting crew killed when a car enters the work zone
1/16/2019	MI	Construction laborer working in highway work zone struck by van.
6/24/2020	MI	Field manager struck by vehicle in active roadway while taking depth measurement.

Source: State FACE Program

PennDOT Crash Data Development

Because national data does not provide detailed crash descriptions, which are needed to identify specific incidents that could be mitigated by technologies, more localized data in Pennsylvania was explored. Based on the Pennsylvania Crash Information Tool (PCIT) Website, 2,185 crashes in active work zones have occurred in the years from 2017 - 2020 were identified. However, with the guidance of PennDOT's Highway Safety and Traffic Operation Division, the crashes were narrowed down to 142 cases that involved vehicles intruding into a highway work zone. The narratives to further understand the cause of the incidents were then reviewed. These 142 cases were then filtered down to 23 cases because the study intends to focus on incidents in which vehicles intruded into construction work zones and highway workers were injured [Khazanovich, 2022]. Table 6 summarizes the accidents reported to PennDOT that involved a highway construction worker injury.

Table 6: PennDOT's Reported Crashes in Work Zones Injuring Highway Workers 2017-2020

Case	Description of Crash and Roadway
1	Flagman was directing traffic and got hit by a truck entering the intersection
2	Operator of the vehicles with arrow signs struck the workers who are working on foot. (a chain of accidents)
3	Worker being hit by a motor vehicle

4	Passenger side of the mirror hit the worker's elbow while he's performing work
5	Vehicle intruded the work zone and clipped the end of the gas line. The gas line then took the worker's leg and caused him to fall onto the pavement
6	Vehicle veered into right closed lane and struck the front bucket of a maintenance front end loader, then hit another worker
7	Vehicle struck 2 workers along with a piece of equipment
8	Vehicle struck a worker and construction barrier
9	Vehicle struck the traffic cones and a worker
10	Vehicle swerved and struck an industrial saw the worker was using
11	Vehicle struck the arrow board while the workers were putting up the construction signs
12	Worker got struck on his nose by a pick hand tool as the vehicle drove over it
13	Vehicle struck a worker who was marking the roadway for joint placement strips
14	Vehicle struck a worker who was performing paving duties and a witness in the work area
15	Worker was struck in the chest by the passenger side mirror of a vehicle
16	A vehicle struck another vehicle in a construction zone, in which the latter vehicle hit a worker.
17	Flagger got struck as vehicles intruded the construction zone
18	Worker got struck in the head as he tried to adjust the traffic cones
19	Vehicle veered off the lane and struck a worker as the driver got distracted
20	Vehicle struck a traffic channelizer which eventually hit a worker working nearby
21	Vehicle intruded an active work zone and failed to stop before hitting a worker
22	Vehicle intruded an active work zone and failed to stop before hitting several workers
23	Vehicle intruded an active work zone and hit a worker after a verbal dispute

Source: Pennsylvania Crash Information Tool

2. Benefit Analysis Results

The ultimate benefit of the implementation of the technology mitigation strategies would be the reduction or elimination of crashes in active work zones injuring highway workers. A review of the base data on injuries developed for Pennsylvania was further reviewed. Based upon the descriptions of the potential crashes that could be mitigated by new technologies and the value of the injuries, benefits were quantified. The quantification was determined based on established benefit analysis methodologies for crash reductions and national data on the quantified value of each worker injury type.

Technologies to Improve Active Work Zone Safety

Three technologies that could conduct pavement inspection and other types of highway construction using remote-control technology were investigated by the Safer Pavement researchers. Considering the practicality of these technologies in Pennsylvania, the technologies were classified into the following groups:

1. Technologies ready for immediate implementation

Automated Real-Time Thermal Profiling for Asphalt Paving based on the Pave IR system - The technology has been approved by many DOTs over the last 15 years as it displays a potential to provide continuous, full coverage and high- quality temperatures data for the operators and inspectors. Nonetheless, additional testing and training, demonstrations and changes to Pennsylvania’s specifications might be required.

2. Technologies requiring additional development, but able to be implemented in the near future

Remote-Controlled GPR (Ground Penetrating Radar) - The use of rolling density meter (RDM) in this technology helps to provide accurate asphalt density information without the need to extract materials (coring) from the constructed pavement. However, there are still challenges with data processing and interpretations which leads to the requirement of further training and modifications to Pennsylvania's specifications. This technology, however, is still under development by MnDOT and anticipates a longer period of time to witness the technology being adopted by PennDOT.

3. Technologies promising significant benefits but requiring substantial enhancements prior to implementation

   Autonomous Impact Protection Vehicle (AIPV) - The technology aims to remove the deliberate risk associated with driving an IPV and it has been proven to have varying degrees of success over the past few years. Therefore, substantial testing and training needs to be implemented in Pennsylvania to aid the growing interest in automated vehicles.

Based upon a review of these technologies it was concluded that the 23 highway worker injuries that occurred in Pennsylvania from 2017 to 2020 had the potential to be mitigated if these technologies were implemented. The next phase of research was to quantify the value of these injury eliminations.

Potential Pennsylvania Highway Worker Injury Reductions

To quantify the potential savings from the crash eliminations due to the use of technologies, information that can determine the average cost of injuries to a highway construction worker when a vehicle enters the work zone was needed. Based on a study conducted back in 2002, A highway work zone injury averaged $9,102 for workers compensation alone, estimated to be 45% of total injury costs [Mohan & Gautam, 2002]. The total cost of the average injury was determined to be $20,227.

Table 7 utilizes the 2002 data and applies it to the 2017-2020 Pennsylvania highway injuries that were determined to be potentially eliminated by the advanced technologies identified in the research project. An inflation factor for medical costs was applied to update the 2002 data [U.S. Bureau of Labor Statistics 2022].

Table 7: Potential Highway Worker Injuries Cost Savings in Pennsylvania 2017-2020

Year	Number of Injuries	Average Cost	Total	Inflation Factor	Present Value
2017	11	$20,227	$222,297	1.6	$355,995.20
2018	4	$20,227	$80,908	1.7	$137,543.60
2019	6	$20,227	$121,362	1.75	$212,383.50
2020	2	$20,227	$40,454	1.82	$73,626.28
Total					$779,548.58

The benefit of identifying technologies that could be implemented to reduce highway worker injuries was determined by evaluating current injuries in the state of Pennsylvania. For the years 2017-2020 a total of 23 injuries occurred in highway work zones at a cost of $779,548.58 to workers. This would be a significant benefit if these technologies were implemented.

IV. Development of Simplified Mechanistic-Empirical Design Tool for Pennsylvania Rigid Pavements

PittRigid ME, gives highway designers a practical tool to select the optimal design parameter combinations in Pennsylvania for concrete pavement sections. The PittRigid ME tool is based upon the Mechanistic-Empirical Pavement Design Guide (MEPDG) and AASHTOWare Pavement ME Design software. The MEPDG method has been shown to product more efficient and equally durable pavement designs than the AASHTO 93 method currently used in Pennsylvania. Use of the Pavement ME software is currently recommended by AASHTO and FHWA . Currently in Pennsylvania the AASHTO 93 method is used for pavement design which can result in less efficient pavement sections when compared to the MEPDG and PittRigid methods. One of the challenges of utilizing ME at a local level is the number of inputs required to perform the design. The PittRigid method streamlines this approach allowing a more efficient computation operation

Using the advanced mechanistic empirical design method (MEPDG), a more cost-effective pavement section, one that is reduced in thickness and that meets the long-term pavement performance requirements can be achieved. The thinner pavement section in turn is anticipated to decrease the construction costs and was documented through various case studies.

The case studies selected compare the selected pavement section design and costs for a reduced design using the PittRigid ME method that provides similar performance at a reduced construction cost. The case studies selected represent the new construction of a major new expressway, reconstruction of a major four lane arterial highway and rehabilitation of an urban collector street.

The PittRigid ME method was used in lieu of the MEPDG design method for these case study designs. The developed design method of PittRigid ME was used because it provides a more localized and efficient design process that encourages use of the method and can result in reduced design thickness and corresponding costs.

1. Baseline Conditions

Baseline conditions represent the current design selected for either construction of a new roadway or reconstruction of an existing roadway. For each of the case studies the current design parameters, from AASHTO 93, and costs were determined by the highway agency responsible for the project. Projects were selected from the Pennsylvania Turnpike Commission, PennDOT and Allegheny County Pennsylvania. These case studies represent a variety of applications for PittRigid ME to demonstrate the benefit that can be derived from use of the design method. The following is a description of each project's baseline conditions, pavement design and costs.

Southern Beltway Washington County Pennsylvania – Pennsylvania Turnpike Commission

The Southern Beltway is a new major expressway being constructed in Allegheny and Washington Counties Pennsylvania by the Pennsylvania Turnpike Commission. The expressway provides a connection from Route 22 to Interstate 70 and is being constructed as a toll road. The project is being constructed in sections designated as Section 55-A1-1, 55-A1, 55-A2, 55-B, 55-C1 and 55-C2). The location of the project and each section is shown in Figure 17.

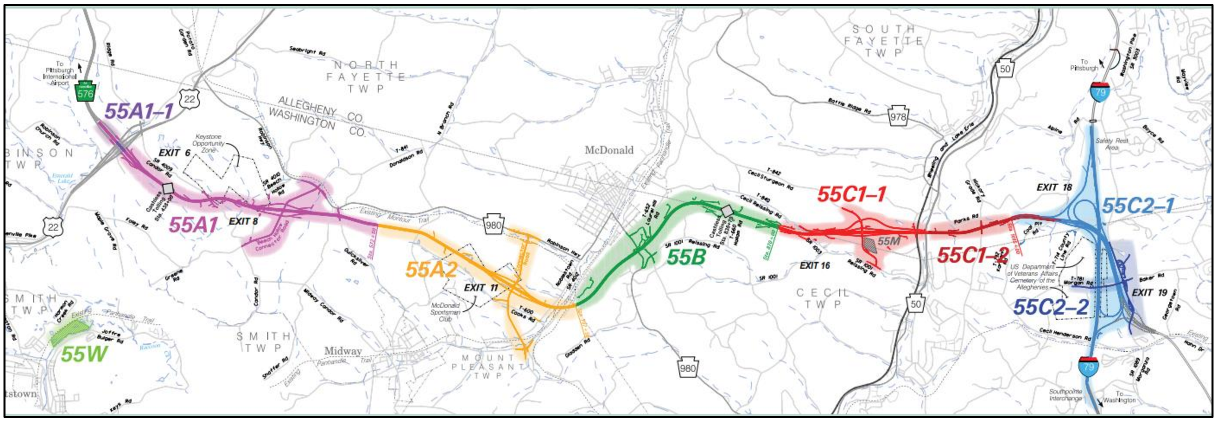


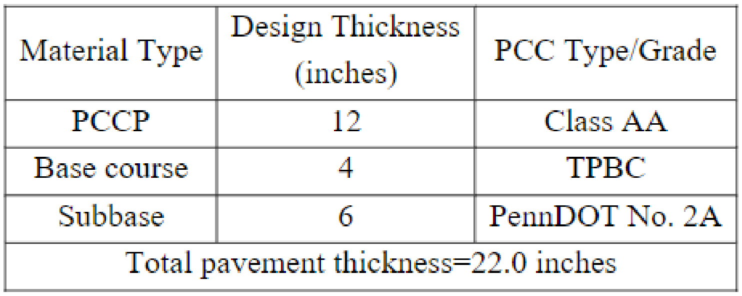
Figure 17: Southern Beltway Project Location and Sections

Source: Pennsylvania Turnpike Commission

The total length of the new construction project pavement is 13.3 miles. This project includes ramped interchanges with U.S. Route 22, Interstate Highway 79 and Morganza Road. The proposed Southern Beltway expressway generally consists of a four-lane highway (two lanes in each direction) with full depth shoulders. The project was recently opened to traffic in October of 2021.

The pavement design that was constructed was based on the soil parameters of the subgrade soil and the volume and types of vehicles expected to utilize the pavement during a 20-year performance period for the initial pavement structure using the AASHTO 93 method as shown in Table 8.

Table 8: Rigid Pavement Design Section Southern Beltway Project US Route 22 to I-79



Material Type	Design Thickness (inches)	PCC Type/Grade
PCCP	12	Class AA
Base course	4	TPBC
Subbase	6	PennDOT No. 2A
Total pavement thickness=22.0 inches		

*PCCP- Plain Cement Concrete Pavement
*TPBC- Treated Permeable Base Course

Source: Pennsylvania Turnpike Commission

The design was performed for the mainline expressway concrete pavement section and is consistent along the entire 13.3-mile length. The ramps and toll plaza are assumed to be the same pavement sections as the mainline. The total quality of pavement area of the four sections of Plain Cement Concrete Pavement (PCCP) was 725,251 SY.

US-119 Westmoreland County – PennDOT District 12-0

The State Route 119 reconstruction work was located in Westmoreland County and East Huntington Township from approximately the County Line (Fayette/Westmoreland) to approximately the median crossover north of the West Tech Drive Interchange for a length of 26,661 feet. The location of the reconstruction project is shown in Figure 18.

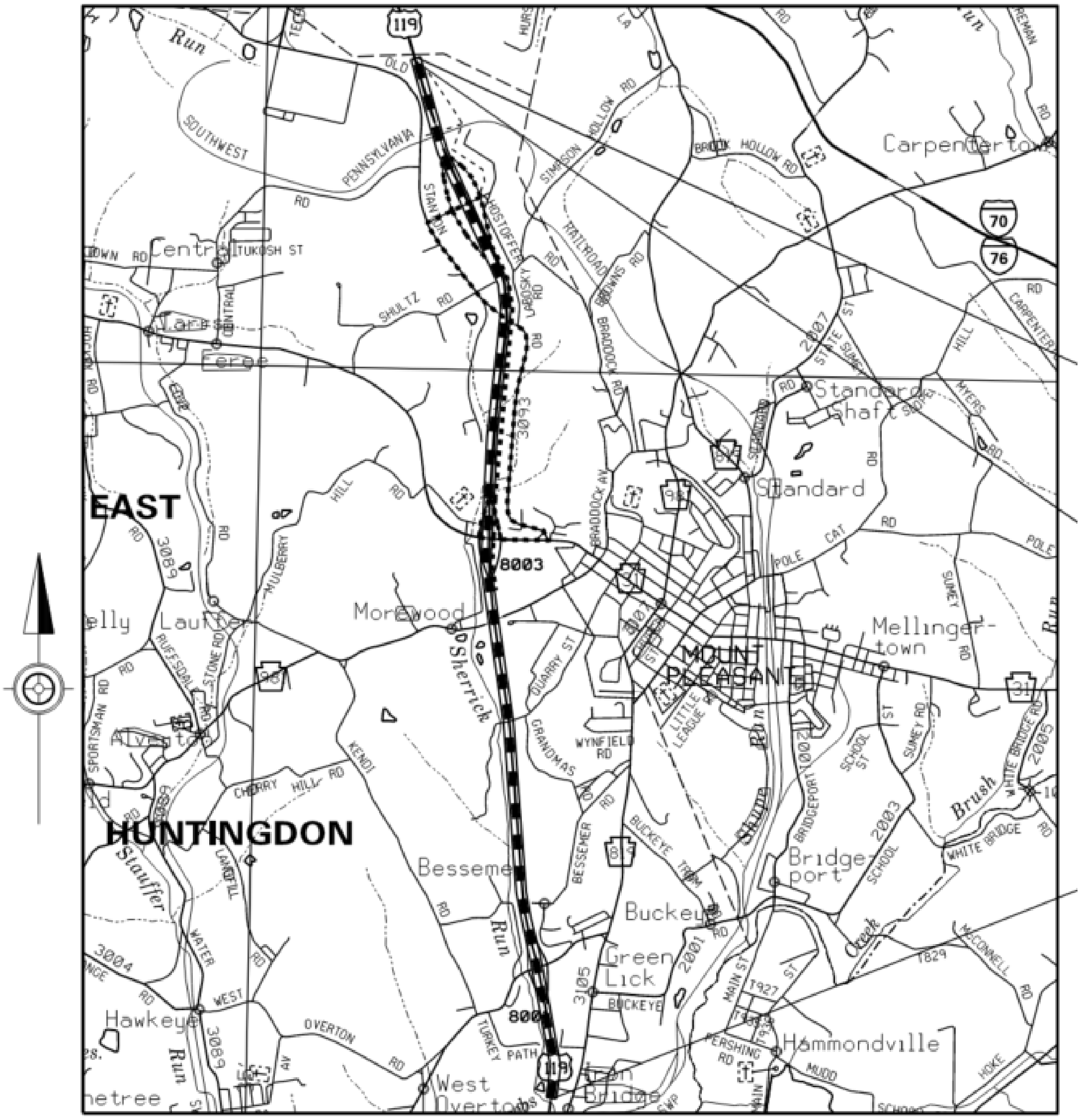


Figure 18: US-119 Project Location and Limits

Source: Pennsylvania Department of Transportation

The completed project includes the reconstruction of both north and south bound lanes, the replacement of the existing grass median with a concrete barrier, the reconstruction of the roadway surface of all ramps at the S.R. 119/ S.R. 0031 Interchange, the lowering of the roadway profile approaching and the bottom bridges that spans over S.R. 119, and other miscellaneous construction. The contract items that was relevant to the research benefit analysis was item 0506-0036 Plain Cement Concrete Pavement RPS that was designed and constructed as a 12” depth. The total quantity of 12” pavement area was 181,885 square yards.

Ivory Avenue City of Pittsburgh – Allegheny County Pennsylvania

The Ivory Avenue project is located on the border of Pittsburgh's Perry North and Summer Hill neighborhoods. Perry Highway (Route 19) and Nelson Run Road were to be closed for 2 months for the reconstruction of the concrete pavement. The location of the project is shown in Figure 19.

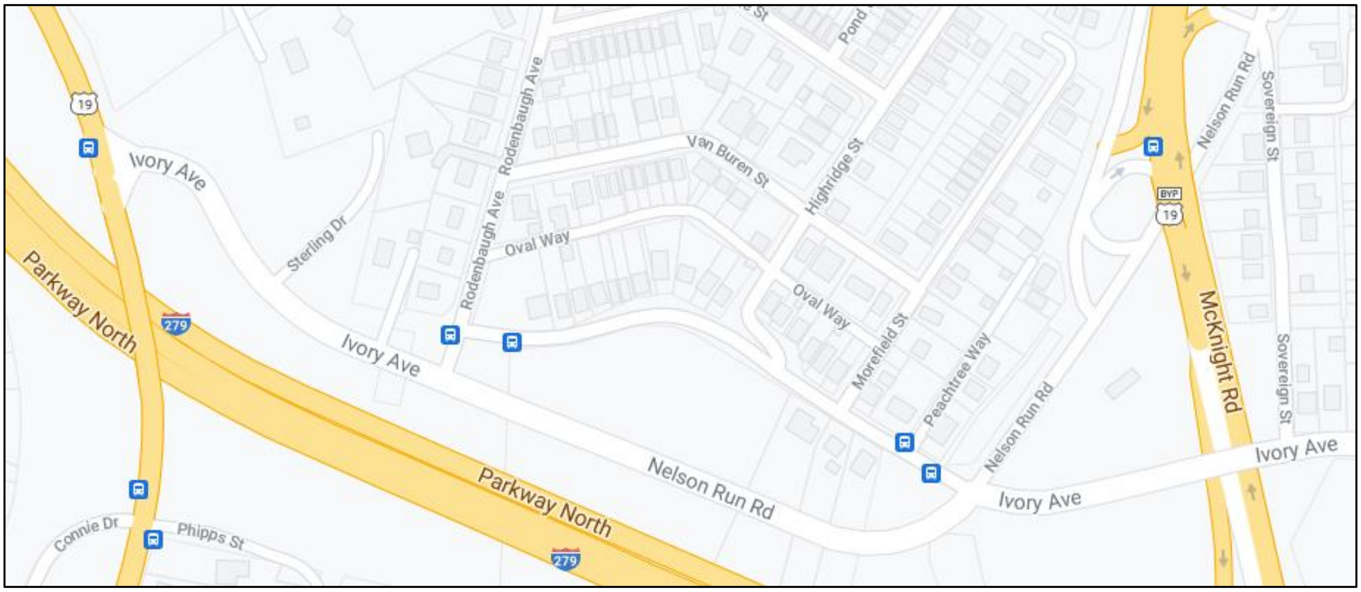


Figure 19: Ivory Avenue City of Pittsburgh Project Locations and Limits

Source: Google Maps

The work was part of the 2017 Capital Roads Reconstruction Project, which was an $8.3 million construction contract to improve eight roads in Allegheny County. The project had a final concrete pavement design of 10 inches of concrete based on the 2015 AASHTO-93 pavement design procedures. The total quantity of concrete pavement reconstruction for this project was anticipated to be 2,475 square yards.

However, after the project was let for construction, the decision was made to overlay the current concrete pavement with bituminous rather than replace the concrete. This project was still utilized as a cases study because it illustrates the potential savings if the PittRigid design was utilized, and a complete reconstruction was performed.

2. Benefit Results

The benefits of utilizing the PittRigid design method for the 3 case studies was determined by performing an alternative design utilizing the IRISE developed design method and comparing the revised design and corresponding construction costs for the three case studies.

After researchers identified the design contract pavement designs, bid items prices and quantities from the three highway agencies for the concrete pavement projects, the data was utilized by IRISE researcher, Dr. Lev Khazanovich, who is the developer of the PittRigid design tool. The PittRigid software was then used to compare the design characteristics for the three case study pavements, which were designed according to the PennDOT Publication 242 2015 edition, to the PittRigid 1.0 model results.

This alternate design was performed by inputting more detailed and different design parameters such as the modulus of rupture (MR) value, roadway traffic patterns, plain cement concrete (PCC) coefficient of thermal expansion (COTE) and other material properties which are more specific in the PittRigid method and are anticipated to result in a more efficient pavement design. Once the design parameters were input, the PittRigid tool produced a result that indicated the suitable concrete thickness for the roadway.

The MEPDG-optimized design recommended the minimum plain cement concrete (PCC) slab thickness for each of the case studies. After rounding the number up, the MEPDG-optimized design reduces the Southern Beltway's PCC slab thickness from the original 12-inch AASHTO design to 9-inches, SR 119's PCC's 12-inch thickness to 8-inches as well as Ivory Avenue's original 10-inch to an 8-inch design. The following Table 9 summarizes the results of the more efficient pavement design and applies that design to the quantities for concrete pavements in each of the case studies.

Table 9: PittRigid Design and Cost Comparison for Case Studies

Project	Original Design Total Unit Price	PittRigid ME Design Total Unit Price	Cost Reduction
Southern Beltway	$44,025,986	$37,422,088	$6,603,898

Plain Cement Concrete Pavement RPS	12 inches	9 inches	
US-119 Plain Cement Concrete Pavement RPS	$10,640,273 12 inches	$9,044,232 8 inches	$1,596,041
Ivory Avenue Plain Cement Concrete Pavement RPS	$210,375 10 inches	$178,819 8 inches	$31,556
		Total	$8,231,495

This analysis revealed that if the PittRigid ME Designs for the three case studies were implemented total pavement construction costs for all three projects would have been reduced by a total of $8,231,495. As shown the benefit of the PittRigid design method is significant for all three case studies which represent different scales of projects. If these savings were applied statewide a very significant savings would be achieved.

V. Material Compatibility Repair

The purpose of the research project was to investigate the extended life of concrete pavement repairs by using repair materials of concrete that are more compatible to the original construction material. Partial-depth repairs are commonly used as a rehabilitation method for deteriorated concrete pavements and bridge decks.

Both partial-depth and full-depth repairs have limited-service life, hence the study developed the best practices to target the problem and extend the service life of the repairs. The methodology selected involves the use of the life cycle analysis methodology from the PennDOT pavement design manual publication 242. This methodology assumes that the new MCR repair method will extend the life of these repairs from their current short service life to the expected 15 years per the manual life cycle methodology.

1. Baseline conditions

Development of the methodology and establishing baseline conditions involved evaluating several potential sources of data and analysis approaches. This section describes how this work evolved into the final methodology and baseline data used.

Route 28 Case Study

As a case study approach the researchers evaluated the Roadway Management System (RMS) as source of determining service life of the current repair method for a selected concrete roadway. Route 28 in Allegheny County was evaluated because it is a concrete roadway with numerous pavement failures. The location is shown in Figure 20.

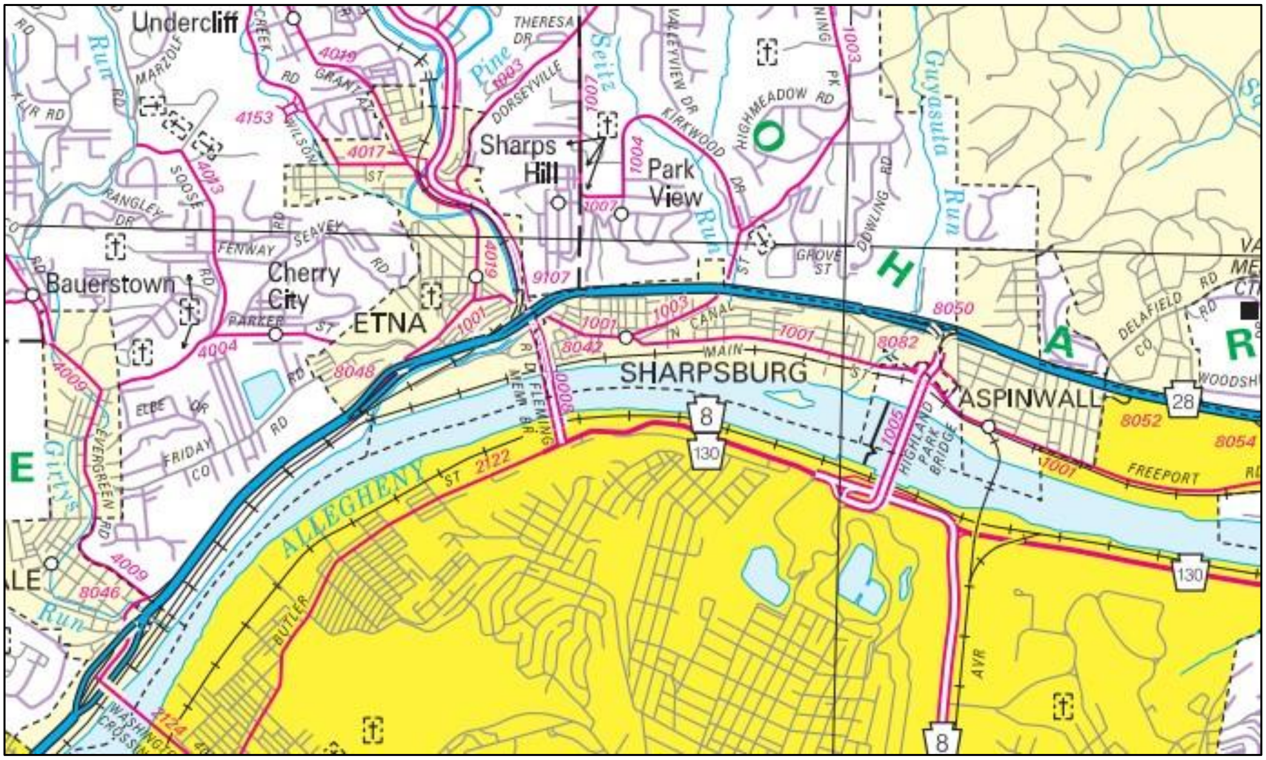


Figure 20: Route 28 Case Study Location

Source: PennDOT Type 10 Maps

The video log of annual inspections was to be used to determine the current service life of several types of pavement repairs. The potential cost savings for a longer service life of the repairs could then be calculated once the past service life was determined.

The goal was to determine when repairs were constructed and then failed by viewing several at each year’s annual pavement inspection photo. However, because the video logs began in 2007 and a major rehabilitation was constructed in 2010, the repairs appeared to be installed before 2007 and evidence of their failure before the reconstruction could not be determined. This is shown in Figures 7 through 10.

While this methodology was promising, the RMS logs for all concrete pavements in Pennsylvania would have to be viewed for repairs that were installed and repaired between 2007 and the present which would determine current service life. This approach did not seem to be feasible. Also, the quality of the videos was not always sufficient to determine the exact year when failure occurred as shown in Figure 21.

Figure 21: Condition in 2009, before MCR Corner Repair
Source: Pennsylvania Department of Transportation

Figure 22: Condition in 2011 after MCR Corner Repair in 2010 and Reconstruction
Source: Pennsylvania Department of Transportation

Figure 23: Condition in 2013 after Reconstruction
Source: Pennsylvania Department of Transportation

Figure 24: Condition in 2018 after Reconstruction

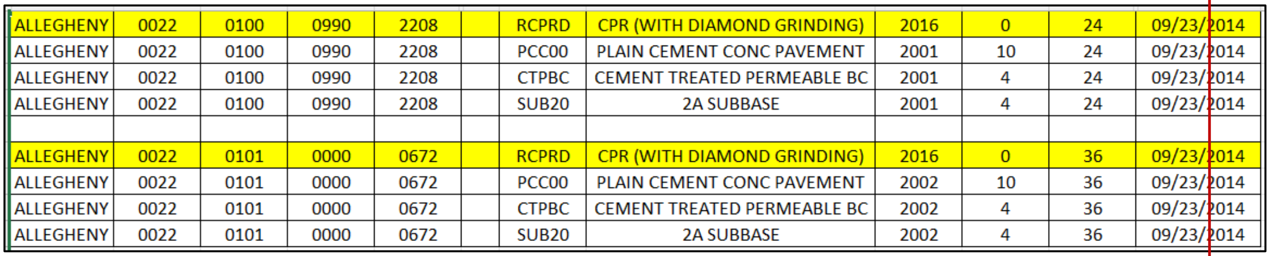
Source: Pennsylvania Department of Transportation

Statewide Pennsylvania Concrete Highway Service Life

A broader approach was also considered to determine what the service life of all concrete pavement repairs in Pennsylvania were by reviewing a database that PennDOT maintains, which documents when major repairs and reconstruction of concrete pavements are performed. The concept was that when major reconstructions are performed the service life of most repairs would have expired. Table 10 is an example of this data from RMS data that PennDOT provided.

As shown in Table 10 for these two example roadway segments, the average time between major reconstructions was 14 and 15 years respectively, however based upon discussion with PennDOT this is not a true measurement of repair service lives because time periods between reconstructions are scheduled based upon available funding not necessary when repairs failed.

Table 10: RMS Concrete Pavement Data SR 0022



ALLEGHENY	0022	0100	0990	2208		RCPRD	CPR (WITH DIAMOND GRINDING)	2016	0	24	09/23/2014
ALLEGHENY	0022	0100	0990	2208		PCC00	PLAIN CEMENT CONC PAVEMENT	2001	10	24	09/23/2014
ALLEGHENY	0022	0100	0990	2208		CTPBC	CEMENT TREATED PERMEABLE BC	2001	4	24	09/23/2014
ALLEGHENY	0022	0100	0990	2208		SUB20	2A SUBBASE	2001	4	24	09/23/2014
ALLEGHENY	0022	0101	0000	0672		RCPRD	CPR (WITH DIAMOND GRINDING)	2016	0	36	09/23/2014
ALLEGHENY	0022	0101	0000	0672		PCC00	PLAIN CEMENT CONC PAVEMENT	2002	10	36	09/23/2014
ALLEGHENY	0022	0101	0000	0672		CTPBC	CEMENT TREATED PERMEABLE BC	2002	4	36	09/23/2014
ALLEGHENY	0022	0101	0000	0672		SUB20	2A SUBBASE	2002	4	36	09/23/2014

Source: Query of PennDOT RMS data 2000-2020 New Concrete Pavement Construction

However, PennDOT did provide the data for all concrete pavements in Pennsylvania and the data was analyzed. The analysis revealed that the average and 85th percentile time period between major reconstructions was determined to be 16 and 32 years, respectively, as shown Table 11.

Table 11: Concrete Pavement Service Life Summary

	Concrete Pavement Service Life Summary (Years)									
	PennDOT Districts									Total
Pavement Data	3-0	4-0	5-0	6-0	8-0	9-0	10-0	11-0	12-0	
Number of Pavement Segments	81	313	18	76	294	70	7	177	152	19,138
Average Service Life in Years (Mean)	21	17	12	13	16	23	13	18	10	16
90th Percentile Service Life in Years	32	25	12	14	22	26	17	26	18	32

Source: Query of PennDOT RMS data from 2000-2020 Major Concrete Pavement Construction

This data analysis indicates that the current service life of all concrete repair methods is significantly shorter than the average time period of 16 years between reconstructions and the repairs are also not meeting the Publication 242 expectation of 15 years. This information provided confirmation of a shorter service life than 15 years for current repair methods. It did not confirm the current service life for the partial depth repairs on a statewide basis therefore a case study approach was investigated to determine current service life.

Concrete Repairs on Routes 22 and 51 Case Studies

The third methodology and baseline data evaluated were two case studies of active projects currently or anticipated to be repaired due to partial depth repair failures. PennDOT and the researchers identified two potential case studies of individual repair failures on Route 22 in Westmoreland County and Route 51 in Allegheny County. The locations of these case studies are shown in Figures 25 and 26.

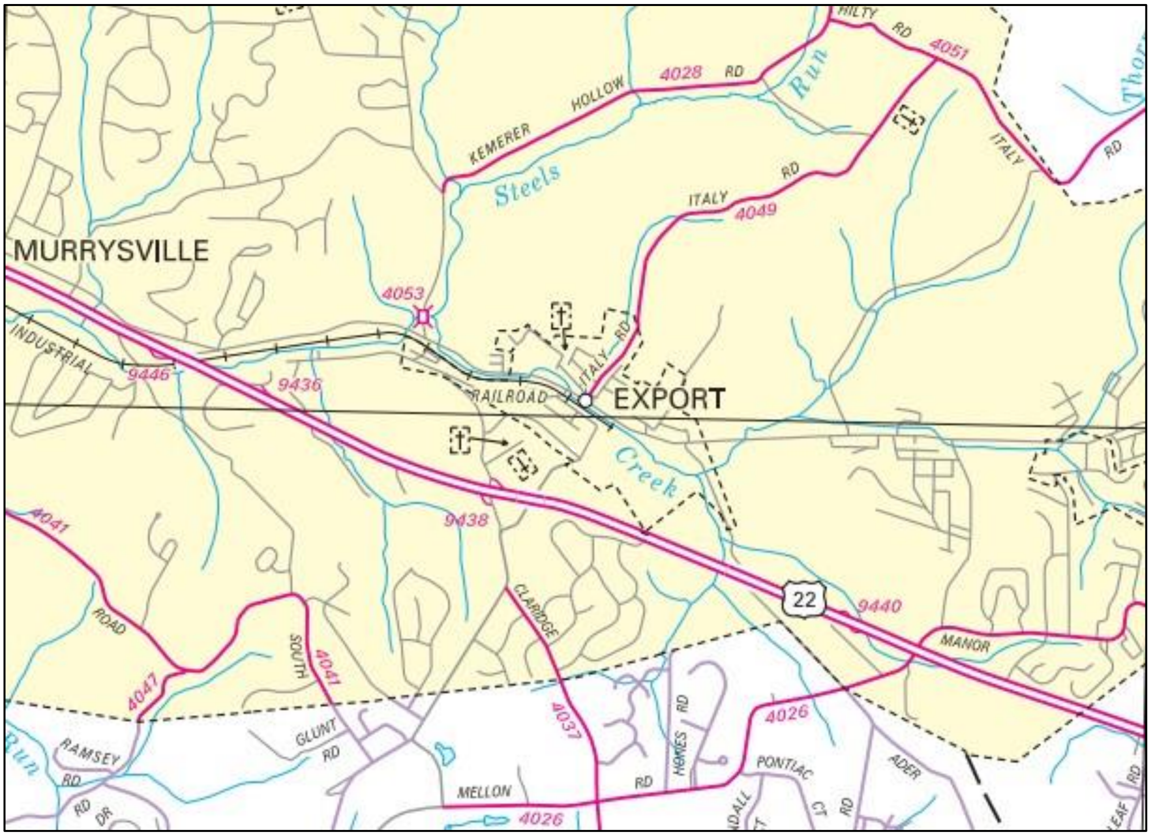


Figure 25: Route 22 Case Study Location

Source: PennDOT Type 10 Maps

Figure 26: Route 51 Case Study Location
Source: PennDOT Type 10 Maps

The goal of this approach was similar to the first case study evaluation which was to determine the service life of the current repair methods by observing repairs that have failed and determining when they had been installed. An in person visit to the sites of these case studies was able to provide a firsthand field inspection of the condition of the repairs.

As shown in Figure 27, a figure from the 2016 construction plans, several different types of repairs were constructed at the same time on Route 51 which included partial depth repairs.

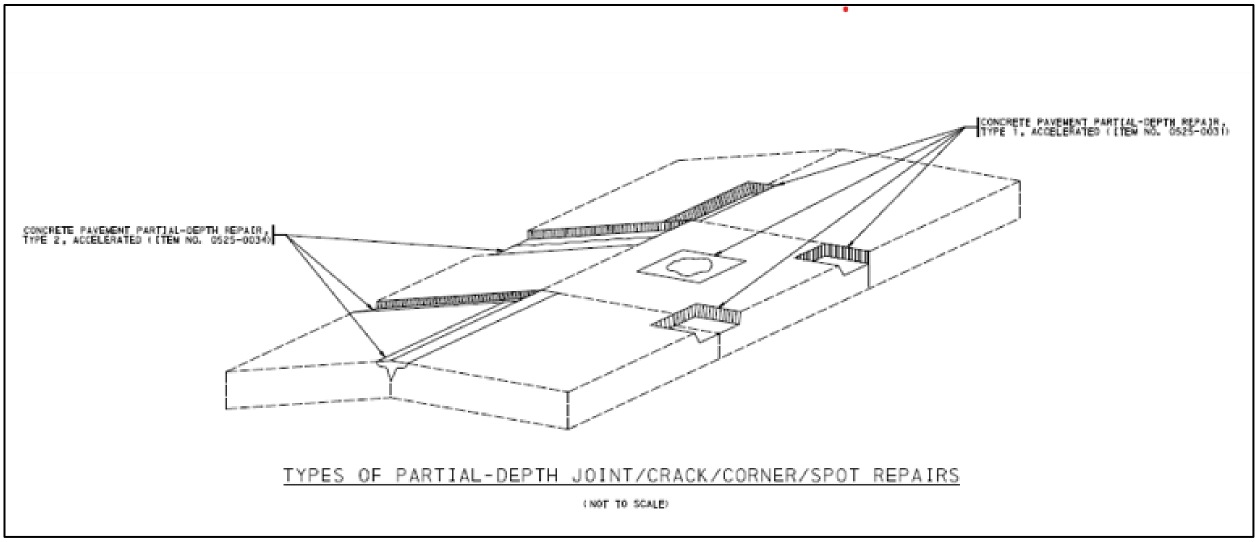


Figure 27: Types of Partial-Depth Joint/Crack/Corner/Spot Repairs

Source: PennDOT, Drawings for Construction, Route 51 Section A94, March 23, 2016

Figures 28 and 29 show partial depth repairs viewed in the field from both Route 22 and Route 51 that have failed at some locations.

Figure 28: Route 22 Partial Depth Repair Intact

Figure 29: Route 51 Partial Depth Repair with Overlay Failure

It is noted that the Route 51 repairs, which were installed in 2019 based upon the construction plans obtained from PennDOT, included partial depth, transverse joint and longitudinal joint repairs with an asphalt overlay installed. Figures 28 through 31 show the failure of these repairs when inspected during the field view in 2022. These failures illustrate both transverse joint and partial depth repair failures.

Figure 30: Route 51 Transverse Repair with Overlay Service Life of 3 Years

Figure 31: Route 51 Transverse Repair with Overlay Service Life of 3 Years

From the Route 22 field inspection no evidence of failures was detected although new repairs were currently in process. From this evaluation of these two cases studies, it was confirmed that the Route 51 partial depth repairs had a service life of less than 3 years.

Selected Methodology and Baseline Data

Because there was limited data available on current service life of repairs both on a statewide and case study basis, PennDOT's life cycle analysis method for pavements was applied to the ECMS data collected for costs of applying the current repair method. It was assumed that the current service life of the MCR repairs is 3 years, and the new repair method would provide a service life of 15 years per the life cycle analysis methods used in Publication 242. This methodology was applied to the baseline data on costs, incurred by PennDOT, for repairs from the ECMS data based. A sample of these costs by items number and the total are shown in Table 12 for the years 2018 to 2020.

Table 12: Concrete Pavement Partial Depth Repairs, ECMS 2018-2020

Item Number	Item Description	Let	Quantity	Unit of Measure	Total Price	Total Price for the item
0525-0030	CONCRETE PAVEMENT PARTIAL-DEPTH REPAIR, TYPE 1, MODIFIED	9/17/2020	1500	SF	$ 86,250	$ 4,414,870
0525-0031	CONCRETE PAVEMENT PARTIAL-DEPTH REPAIR, TYPE 1, ACCELERATED	9/26/2019	300	SF	$ 36,000	
0525-0032	CONCRETE PAVEMENT PARTIAL-DEPTH REPAIR, TYPE 1, RAPID-SET	6/13/2019	36885	SF	$ 2,545,065	
0525-0034	CONCRETE PAVEMENT PARTIAL-DEPTH REPAIR, TYPE 2, ACCELERATED	9/26/2019	300	SF	$ 28,500	
0525-0035	CONCRETE PAVEMENT PARTIAL-DEPTH REPAIR, TYPE 2, RAPID-SET	1/16/2020	350	SF	$ 32,200	
0525-0036	CONCRETE PAVEMENT PARTIAL-DEPTH REPAIR, JOINT SEALING	12/13/2018	24	LF	$ 840	

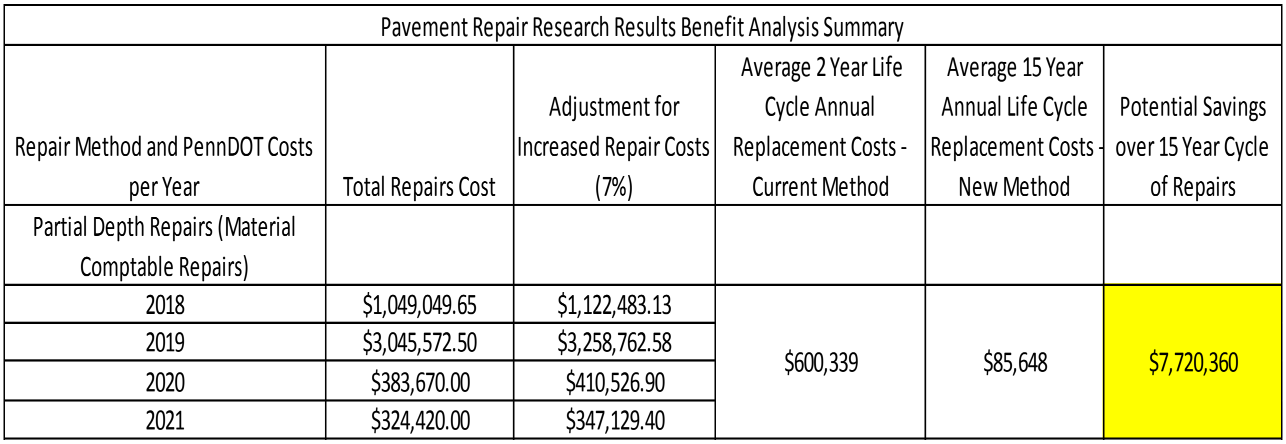
Source: ECMS

2. Benefit Results

The final selected methodology of utilizing the life cycle analysis method from the Pavement Design Manual and statewide baseline data from ECMS was applied. However, the new repair method costs require an adjustment for increased future repair costs of 7%, which was determined through the Material Compatibility Repairs (MCRs) for Concrete Pavements and Bridge Decks research study. This added expense would allow for the service life to be extended enough to provide significant benefit with the additional construction cost. The increase in service life allows for economic savings for the MCR repair using an improved construction method to be used statewide. Additionally, better ride quality, safer travel, and a decrease in closure time were considered user benefits of the study as well.

As shown in Table 13 a total of $7,720,360 was determined as the potential savings over a 15-year cycle of repairs statewide for the 4-year period studied. The analysis determined the current average service life of the MCR repair method from PennDOT experience and limited case studies of MCR repair projects.

Table 13: Benefit Analysis Summary of Pavement Repair Research Results



Pavement Repair Research Results Benefit Analysis Summary					
Repair Method and PennDOT Costs per Year	Total Repairs Cost	Adjustment for Increased Repair Costs (7%)	Average 2 Year Life Cycle Annual Replacement Costs - Current Method	Average 15 Year Annual Life Cycle Replacement Costs - New Method	Potential Savings over 15 Year Cycle of Repairs
Partial Depth Repairs (Material Comptable Repairs)					
2018	$1,049,049.65	$1,122,483.13	$600,339	$85,648	$7,720,360
2019	$3,045,572.50	$3,258,762.58			
2020	$383,670.00	$410,526.90			
2021	$324,420.00	$347,129.40			

In summary the analysis determined the current average service life of the MCR repair method from PennDOT experience and limited case studies of MCR repair projects. The Pavement Design Manual expectations on repair service lives for concrete pavements was assumed for future service life of the new MCR repair method. The potential savings were found to be a total of $7,720,360 for a four-year period. This benefit of Material Compatibility Repairs is significant for the statewide costs currently incurred as well as the future of pavement repairs, both extending the service life and creating long term economic savings.

Summary

This report provides the results of the benefit analysis for the five projects performed by IRISE. The first task performed as part of this research effort was a literature review. Current methodologies were evaluated to predict changes in highway infrastructure relative to longevity and resulting cost reductions due to innovations resulting from research. These existing methodologies, novel methods or new practices that were developed were considered for IRISE research projects based upon successful and meaningful results.

During the next task, each of the projects was examined in detail to determine what types of unique benefits may be expected. It was determined that the benefits can be quantified based upon direct and indirect impacts.

As shown the benefits are significant. Based upon case studies performed reduced costs were projected in an individual project basis. Cost savings based upon overall project costs in Pennsylvania for related construction items were also substantial. This is a summary of the results for each of the five projects:

I. Early Opening to Concrete Pavements to Traffic

A user cost analysis in the research study showed that early opening pavement to traffic would have significant benefits on urban arterial roadways. An analysis of a hypothetical construction project involving an urban street closure was performed to demonstrate the potential vehicular user benefits of opening it to traffic earlier than a typical construction project would permit. This user benefit analysis showed that street closures due to work-zones in Pittsburgh Downtown can save user delay costs of $123,645 per day

In a separate construction case study provided by Golden Triangle Construction, a portion of State Route 837 was originally bid to be constructed with high early strength (HES) concrete. The reduction in the cost of the specified concrete was quantified by comparing the normal strength PennDOT class AAPAVE mix, which was testing using the research methods to determine strength to using the HES mix. This translated to a total cost benefit of $40,950 by using the normal strength PennDOT class AAPAVE mix in lieu of the HES mix.

II. Preliminary Evaluation of Pavement Surface Distresses Related to Pavement Marking

This research project studied pavement sections along the longitudinal joints exhibiting distresses and identified the cause of the problem to determine if it arises from the pavement markings. It was determined that the pavement markings do not deteriorate the longitudinal joints, however other factors that impact the joint result in a repair process that requires removal and reinstallation of the markings.

Based on the case studies of recently repaired major highways in PennDOT District 11-0, the potential savings for reapplication of longitudinal pavement markings could be $1,937,772 for thermoplastic application for the two case studies evaluated.

III. Remote-Controlled Technology Assessment for Safer Pavement Construction and QA/QC

Implementation of technologies will improve the safety and efficiency of construction activities in this higher-risk work area. The primary benefit is fewer worker injuries in the higher danger sections of work zones due to vehicle intrusions. Crash and worker injury data related to vehicles entering the work zone and injuring highway construction workers that could be mitigated by remote-controlled technologies was identified.

The benefit of identifying technologies that could be implemented to reduce highway worker injuries was determined by evaluating current injuries in the state of Pennsylvania. For the years 2017-2020 a total of 23 injuries occurred in highway work zones at a cost of $779,548.58 to workers. This would be a significant benefit if these technologies were implemented

IV. Development of Simplified Mechanistic-Empirical Design Tool for Pennsylvania Rigid Pavements

Using the advanced mechanistic empirical design method (MEPDG), a more cost-effective pavement section, one that is reduced in thickness and that meets the long-term pavement performance requirements can be achieved. The thinner pavement section in turn is anticipated to decrease the construction costs and was documented through various case studies.

For each of the case studies the current design parameters, from AASHTO 93, and costs were determined by the highway agency responsible for the project. Projects were selected from the Pennsylvania Turnpike Commission, PennDOT and Allegheny County Pennsylvania. These case studies represent a variety of applications for PittRigid ME to demonstrate the benefit that can be derived from use of the design method. The following is a description of each project's baseline conditions, pavement design and costs.

This analysis revealed that if the PittRigid ME Designs for three case studies were implemented total pavement construction costs for all three projects would have been reduced by a total of $8,231,495. The benefit of the PittRigid design method is significant for all three case studies which represent different scales of projects. If these savings were applied statewide a very significant savings would be achieved.

V. Material Compatibility Repair

The purpose of the research project was to investigate the extended life of concrete pavement repairs by using repair materials of concrete that are more compatible to the original construction material. Partial-depth repairs are commonly used as a rehabilitation method for deteriorated concrete pavements and bridge decks.

PennDOT's life cycle analysis method for pavements was applied to the ECMS data collected for costs of applying the current repair method. It was assumed that the current service life of the MCR repairs is 3 years, and the new repair method would provide a service life of 15 years per the life cycle analysis methods used in Publication 242. This methodology was applied to the baseline data on costs, incurred by PennDOT, for repairs from the ECMS data based

The potential savings were found to be a total of $7,720,360 for a four-year period. This benefit of Material Compatibility Repairs is significant for the statewide costs currently incurred as well as the future of pavement repairs, both extending the service life and creating long term economic savings.

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