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Decision Support Tools for Multi-objective, Multi-asset, Multimodal Joint Maintenance Programming

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16. Abstract

Infrastructure assets, such as roadways, bridges, tunnels, railways, and intermodal terminals, are components of a larger transportation system serving competing goals of drivers, passengers, and freight. While transportation elements are typically managed by category, this can have beneficial or detrimental consequences for services provided across categories as well as for asset performance lives. This project explores opportunities for asset management coordination and develops quantitative capabilities for assessing their effectiveness. The techniques will support tradeoff analyses and prioritization in this multi-objective, multi-decision-maker, and multimodal setting. Case studies involving multi-objective, multi-attribute and multimodal tradeoffs when infrastructure repairs and improvements are undertaken were developed. The case studies revealed the complexity of issues, the many different objectives, and the reliance on experience to integrate multi-objective, multi-attribute and multimodal tradeoffs into decision related to maintenance programming. This project demonstrated the importance of agencies paying attention to the disruption caused to all modes of transportation. Increased interest in non-motorized modes of transportation as a strategy to support sustainable mobility and access is slowly encouraging more users and the mode share of non-motorized modes and becoming significant. Bicycle and pedestrian facilities have been shown to contribute to the changes. However, long-term success requires consideration of how the facilities will be maintained and how to mitigate the disruptions that will occur when shared facilities are maintained or improved.

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Infrastructure assets, transportation system, asset management, repairs, improvements, maintenance, sustainable mobility

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CHAPTER 1

Introduction

BACKGROUND

Infrastructure assets, such as roadways, bridges, tunnels, railways and intermodal terminals, are components of a larger transportation system serving competing goals of drivers, passengers and freight. While transportation elements are typically managed by category (e.g., roadways separately from bridges), the effect of investment or lack thereof in any element within one category can have beneficial or detrimental consequences for services provided across categories, as well as for asset performance lives. This is because these systems are interconnected; thus, a change in capacity in one service (e.g. highways) can affect both the functionality of services provided by another (e.g. railways) and the demand across them. This may lead to unanticipated and detrimental impacts on infrastructure condition. Despite these interconnections, these assets are often separately owned, operated and managed.

OBJECTIVES

This project explores opportunities for asset management coordination and develop quantitative capabilities for assessing their effectiveness. The techniques will support trade-off analyses and prioritization in this multi-objective (e.g. minimizing user delay while maximizing asset longevity), multi-decision-maker (aligning actions across assets) and multi-modal (road, rail, and intermodal terminals) setting.

RESEARCH APPROACH

The project initially explored case studies from U.S. cities illustrating multi-objective, multi-asset, multi-modal tradeoffs to understand the objectives considered, the types of tradeoffs and impacts on different modes. Chapter 2 documents a variety of case studies and Chapter 3 documents a detailed case study related to the closure on the I-495 bridge across the Christina River.

As the case studies were developed, the project team explored opportunities for research related to multi-modal multi-objective tradeoffs in the context of the projects. Examples considered included tradeoff decisions related to highway and rail facilities, freight versus passengers, agency costs and user costs, access to intermodal facilities such as ports, and facilities supporting non-motorized modes of transportation.

The team agreed to focus on the tradeoffs involved in maintaining urban streets and the related bicycle/ pedestrian network. Challenges to be addressed include the modeling of the network to reflect travel times for different classes of users and the bundling of projects to account for disruptions. This focus has also required the completion of the following tasks:

- Ascertain and document the state of the art and practice related to maintenance and rehabilitation activities specific to physical characteristics and interactions among modes, usage and operations across pavements and facilities that support non-motorized modes of transportation.
- Study the advantages in terms of overall system health from selected alternative strategies that are possible for completing repairs or maintenance actions on roadways and bicycle and pedestrian facilities, the staging of these actions given plans associated with other modes, their timing and corresponding durations (some activities may require shorter durations if

completed at night, for example) on system performance of the studied modes for both passenger and goods movements.

- Define potential actions and impacts of taking a multi-objective, multi-asset, multi-modal perspective.
- Identify relevant performance measures.
- Based on a synthesis of the findings identify models, data, and potential case studies for model development.
- Develop a network model to predict travel time for each mode.
- Building on the multi-modal network conceptualization, develop mathematical techniques that determine optimal or Pareto-optimal maintenance and rehabilitation scheduling for a given mode and asset considering related plans from other modes and assets and the sometimes-competing goals of multiple stakeholders.
- Develop the case study and ascertain the potential benefits of the application of the tools to the study area.

RESEARCH PRODUCTS

In addition to this report, several other research products in the form of papers, presentations, a thesis, and a class project have been produced.

The following paper is in preparation:

- Chen, Q., E. Miller-Hooks, McNeil, S., S. Stoffels, P. Hu, Y. Liu "Shared Automobile, Bicycle, and Pedestrian Facilities: Evaluating the Impact of Maintenance Actions on Diverse Users," in preparation for submission.

The following papers have been presented:

- McNeil, Sue, Qiang Chen, Pengsen Hu, Yuanchi Liu, Elise Miller Hooks, Shelley Stoffels, "Performance Measures to Support Maintenance Decisions for Shared Auto, Bike and Pedestrian Facilities in the Context of the Lifecycle of a Socio-Technical System," ASCE International Conference on Transportation & Development (ICTD 2022), Seattle, May 2022. https://doi.org/10.1061/9780784484364.013 (This paper is part of Chapter 4.)
- Withers, Alexis, Earl E. Lee, II, Shen-Chang Lin and Sue McNeil, "Control, Monitor, and Inform: Lessons Learned from the 2014 Delaware I-495 Emergency Bridge Closure," Transportation Research Board Annual Meeting, 2022. (This paper is developed from Wither's thesis and is part of Chapter 3.)
- McNeil, Sue, Yuanchi (Daniel) Liu, Shelley Stoffels, Elise Miller-Hook, Pengsen (Jason) Hu, Qiang Chen, "Shared automobile, bicycle, and pedestrian facilities: Toward a multi-objective approach to selecting maintenance actions" (extended abstract), Australian Transport Research Forum, December, 2021. (This paper is part of Chapter 4.)

The following abstract has been accepted for presentation:

- Hu, Pengsen, Shelley Stoffels, Multimodal Transportation Infrastructure Project Bundling in Urban Areas

The following talks have also been given:

- McNeil, Sue. "Maintaining Shared Auto, Transit, Bike and Pedestrian Facilities," Australian Institute of Traffic Management and Planning 2021 Online Conference, September-October, 2021.
- McNeil, Sue. "Maintaining Shared Auto, Transit, Bike and Pedestrian Facilities," rCITI Seminar, University of New South Wales, March 2022.
- McNeil, Sue. "Enhancing Situational Awareness of Traffic Impacts During Highway Emergency Closure: Opportunities Presented by the I-495 Bridge Closure in Delaware," University of Sydney, November 2020.

The following University of Delaware MCE Thesis was completed as part of this research:

- Withers, A. Tradeoffs in Transportation Repair and Rehabilitation Decision-Making: A Case Study of the Delaware I-495 Bridge Repair. Master of Civil Engineering Thesis, University of Delaware, May 2021. (part of Chapter 2 and Chapter 3)

The case study also served as a foundation for the Advanced Infrastructure Management Bootcamp class project in 2021.

OUTLINE OF THE REPORT

The report outline is as follows:

- Chapter 1, this chapter, introduces the project and provides some background as well as documenting the objectives. The products of this research are also described.
- Chapter 2 provides a brief literature review and presents three case studies involving multi-objective, multi-modal tradeoffs.
- Chapter 3 is an extensive review of the repair of the I-495 bridge in Delaware and the tradeoffs involved.
- Chapter 4 describes the multi-objective challenges presented when repairing, maintaining, and upgrading bicycle, pedeetrian and automobile facilities. The chapter inclues a literature review, potential performance measures, a descriptive problem formulation and a description of the case study.
- Chapter 5 describes an enhanced network model that details mode changes, and places where modes share facilities.
- Chapter 6 explores the impacts of project bundling included detailed experiments.
- Chapter 7 documents an alternative heuristic method for scheduling projects.
- Chapter 8 details the travel time and safety models for diverse travelers.
- Chapter 9 presents findings and recommendations.
- Five appendices document the data needed to support the analysis for the case study. Appendix A is the link and origin-destination data. Appendix B is the pavement condition data. Appendix C is the detailed input data for the enhanced network model. Appendix D contains the project data for the case study. Appendix E contains the risk scores for the arcs in the example network.

CHAPTER 2

Case Studies

This chapter explores a variety of case studies intended to illustrate multi-objective and multi-modal tradeoffs when a transportation facility is closed due to a failure or planned repair or rehabilitation.. The chapter is organized into four sections. Section one reviews multi-modal, multi-attribute, multi-objective, and multi-asset tradeoffs that occur when making repair, maintenance, and rehabilitation decisions. Next, section two discusses bridge failures in the U.S. with an emphasis on performance ratings, aging infrastructure, and federal and state standards to illustrate the breadth of experiences with bridge failures, the extent to which such failures cause disruption, and the costs of disruption and repair. Section three presents three cases studies: the CTA Green Line repair and rehabilitation project, the I-710 Long Beach Freeway accelerated rehabilitation, and the I-495 emergency bridge closure in Wilmington, Delaware. Last, section four is a synthesis of all sections and summarizes the research presented in this literature review chapter.

MULTI-MODAL, MULTI-ATTRIBUTE, MULTI-OBJECTIVE, & MULTI-ASSET TRADEOFFS

A multi-modal tradeoff is characterized by multiple (several different) modes. Oftentimes in the realm of transportation, multi-modal refers to the transport of people or goods “using more than one different mode of transportation” (What is Multimodal Transport, 2019). Goods use multi-modal transport via train, cargo ship, airplane, tractor trailer, ground transportation, postal service, etc. In most cases, the transport of goods is managed by a Multi-modal Transport Operator (MTO) who facilitates the transport of commodities “from one point of origin to its final destination” (What is Multimodal Transport, 2019). In the context of this thesis, multi-modal can also refer to the transport of people via public transportation such as bus, rail, car, bike, and/or walking. This is where multi-modal tradeoffs arise.

In a hypothetical scenario let’s analyze the multi-modal travel of Commuter A, Commuter B, and Commuter C, all of whom are traveling from the same origin point to the same destination. Commuter A spends $20 in gas and tolls to drive the entire way and has a travel time of one and a half hours. Commuter B decides to bike to the nearest train station, spends $8 to catch the train, then spends $3 to ride the streetcar to the destination and has a travel time of two hours. Commuter C spends $3 in gas and parking to drive to the bus station, spends $5 to catch the bus, then walks to the destination and has a travel time of an hour and forty-five minutes. The multi-modal tradeoffs presented in this scenario are access mode, transit mode, cost, and travel time. When considering different modes of transport, individuals are presented a unique set of tradeoffs to consider. The use of public transportation is a means of mass transport and may also “help advance various environmental, health, and congestion-mitigating benefits for communities” (Multimodal Access to Public Transportation, 2015). There is a bit of a grey area between the typical car transport and public transportation systems – the key is access. According to the U.S. Department of Transportation (USDOT), “the idea is that providing the infrastructure and support services for multiple modes of public transportation will increase use of the public transportation system and result in health benefits (Multimodal Access to Public Transportation, 2015). Overall, to increase multi-modal transport, it is necessary to provide access to public transportation systems and as a result, multi-modal tradeoffs are presented.

By definition, a multi-attribute decision refers “to making preference decisions by evaluating and prioritizing a limited set of alternatives based on multiple conflicting attributes” (Zhang, 2014). Multi-Attribute Value Theory (MAVT) is used to address problems with various conflicting objectives, which are comprised of multiple attributes. Analyzing the attributes, a performance measure is obtained to compare the varying alternatives that align with the overall objective. Mathematically, a utility or 'U' function is created "to transform the attributes of each alternative policy into one single value" (Multi-Attribute Value Theory). The best valued alternative is selected and represents the preference of the decision maker (Multi-Attribute Value Theory). In the context of this thesis, the multi-attribute tradeoffs presented include traffic impact, construction duration, project cost, stakeholder input, access, user disruption, additional travel time cost, and economic return. For instance, a rail agency may have plans to close a station due to a decrease in economic return. However, stakeholders (such as rail users or even station employees) join hands and lobby for the station to remain open as its essential for their everyday life. In this scenario all of the above referenced multi-attribute tradeoffs can be considered. How much will it cost to keep the station open? Will enhancing the station generate more income? Will there be an economic return if the rail agency enhances the station? Multi-attribute tradeoffs are essential in project decision making and determine the best way forward.

The term multi-objective refers to various conflicting attributes that present various and oftentimes conflicting goals (objectives). Multi-objective problems are solved using multi-objective optimization (MOO). "Multi-objective optimization has been applied to many fields of science, including engineering, where optimal decisions need to be taken in the presence of tradeoffs between two or more objectives that may be in conflict" (Chang, 2015). Essentially, MOO involves various objective functions and either minimizes or maximizes the functions to consider the optimal (or best) set of constraints. The result is a set of solutions that determines which objective returns the best tradeoffs. A successful MOO provides a diverse set of solutions to ensure all attributes are considered (Chang, 2015).

In the context of this thesis, multi-objective tradeoffs refer to access, mobility, environmental impacts, and economic development. Access refers to how easy it is for users to get to/from a transit center and also factors in travel time. Mobility refers to how many users can be moved around at once, to maximize efficiency (think mass transport). Environmental impacts refer to overall system efficiency and sustainability (emissions). Last, economic development refers to job opportunities and economic growth (often expresses as percentage growth of economic indicators. For example, if an agency is considering the construction of a transit center and wants to maximize access, mobility, and economic development while minimizing travel time and negative environmental impacts, the agency should perform a MOO analysis. All objectives, whether maximized and minimized, are analyzed to present a diverse set of solutions. These set of solutions could impact the location of the transit center and what modes of transport, services, and jobs that are offered at the transit center. Overall, multi-objective tradeoffs present the best solution.

Last, multi-asset (cross-asset) refers to the "decision making process by which resources from one asset class are transferred to another to maximize perceived utility (Defining Cross-Asset Decision Making, 2016)". In this context, unlike the tradeoffs mentioned above, perceived utility does not refer to a mathematical computation. Instead, it refers to how an agency perceives the need of an asset and how it can result in transferring resources amongst various projects. To determine the need of an asset a cross-benefit analysis, multi-criteria decision analysis, and/or risk-reward based analysis can be explored. The cost-benefit analysis is used to determine the cost of each benefit. The multi-criteria decision analysis uses a utility function to "assign values to dissimilar attributes" and produce a prioritized list of options (Defining Cross-Asset Decision Making, 2016). Finally, the risk-reward based analysis factors risk into benefit calculations which overall determines the best benefit in terms of presented risk.

In the context of this thesis, a multi-asset (cross-asset) tradeoff refers to the investment, time, and resources used to improve transportation infrastructure and to accommodate users. For instance, traffic cameras and Bluetooth detection devices are key assets that DelDOT uses to monitor and control traffic within Delaware's transportation system. Say DelDOT wants to increase the number of Bluetooth detection devices across the state in order to efficiently collect real-time traffic data. To do this, DelDOT will need to consider the cross-asset tradeoffs. DelDOT may need to consider pulling funding from traffic cameras to meet the funding requirements. Of the detection devices. DelDOT may perceive that the need for Bluetooth detection devices is greater than the need for traffic cameras because the Bluetooth devices manually generate raw vehicle data whereas traffic cameras would still require an engineer to monitor the site. It is also important to note that infrastructure users are also assets and key stakeholders in transportation projects. The objective of many transportation projects is to improve overall efficiency while accommodating road users and maintaining a budget.

U.S. BRIDGE FAILURES

Design and structural deficiencies, construction defects, accidental overload, poor material quality, and poor maintenance are the most common cause of bridge failure. Design deficiencies are a result of mistakes in the conceptual plan of a bridge such as detail designs. Details are ultimately constructed and approved by professional licensed contractors and engineers; however, the deficiency appears in the construction phase. What the contractor and engineer designs is not always what the construction crews implement or install. This is where we see workmanship challenges and an overall deviation in plans and specifications (Wardhana & Hadipriono, 2003).

Additionally, bridge failures are also commonly caused by extreme events including extreme loads, blasts, fires, and natural disasters such as a hurricane, tornado, landslide, flood, and earthquake. In fact, an Ohio State University graduate student determined that, out of 503 U.S. bridge failures, the most frequent causes “were attributed to floods and collisions” (Wardhana & Hadipriono, 2003). Regarding the occurrence of bridge failure, it was determined that eight out of 503 bridges failed during the construction phase, 386 during service, and 109 unknowns. Out of the bridges that failed during service, 17 were caused by distresses, 80 from partial closures, 12 from total collapses, and 277 were unknown (Wardhana & Hadipriono, 2003). Relating this data to the I-495 bridge closure, bridge 1-813 experienced failure during service, which primarily resulted in distresses caused by the tilting of columns and piers. Thankfully, DelDOT caught the issue before the distresses worsened and there was no collapse and there was no loss of human life. However, other bridges (and road users) were not so lucky.

Table 2-1 summarizes just a few bridge failures within the U.S from 2001 to 20018 providing a date and location of occurrence, description of the bridge failure, and the traffic impact of the failure.

Specific to the state of Delaware, where the I-495 emergency bridge closure took place, a 2016 study provided by Reason Foundation determined that Delaware was ranked #42 (out of the 50 states) for overall highway performance. To determine these performance rankings, state highway system budgets are compared to overall system performance and rankings are established. In this analysis, factors such as climate, truck volumes, state budgets, population, and urbanization were key components in determining Delaware's performance ranking. On a positive note, Delaware is ranked #6 in the structurally deficient bridge category. To determine this percentage, the National Bridge Inventory (NBI) is analyzed to determine the average bridge condition within the state. The bridge closure occurred in 2014 and the data in this study was based off 2016 data. Relating this to the I-495 bridge, this is great information for the state of Delaware as it can be implied that the I-495 bridge deficiencies impacted planning and potentially lead to such a high ranking (Feigenbaum, Fields, & Purnell, 2019). In general, although Delaware received a poor ranking for overall highway performance (42 out of 50), the state did receive a good ranking for structurally deficient bridges (6 out of 50).

The U.S. Department of Transportation's Federal Highway Administration (FHWA) published its most recent version of the National Bridge Inspections Standards Regulation (NBIS) in December of 2004 with a final revision added in 2009 (Bridges & Structures, 2020). The goal of the 2004 update was to "clarify the NBIS language that is vague or ambiguous; recognizes the NBIS into a more logical sequence; and makes the regulation easier to read and understand" (Federal Register, 2004). Taking effect on January 13, 2005, the NBIS required State and Federal agencies to establish criteria for inspection level and frequency, systematic quality control (QC) and quality assurance (QA), and procedures to follow-up on critical findings by April 2005. Ultimately, "the primary purpose of the NBIS is to locate and evaluate existing bridge deficiencies to ensure the safety of the traveling public" (Bridges & Structures, 2018). Additionally, for clarification, the NBIS only covers twenty feet or longer highway bridges on public roads that are publicly owned. In other words, although private highway bridges do exist, States are only required to report on public bridges. Overall, the NBIS terms require inspections for all highway bridges that meet the previous stated requirements and are open to the general public (Bridges & Structures, 2018).

Table 2-1 Select Bridge Failures in the U.S. from 2001 to 2018

Date/Location	Bridge Failure	Traffic Impacts
9/15/2001 Queen Isabella Causeway, South Padre Island, Texas (Tyrrell, 2001)	Partial collapse A 160-foot section of the Queen Isabella Causeway collapsed after a barge stuck the structure. Twelve hours later another section of the bridge collapsed. As a result, vehicles plummeted into the Laguna Madre, killing 8 and injuring 13.	Closure duration: 2 years. Since the bridge was the only connection from South Padre to the mainland, vehicles were transported across the laguna via boat. There were severe travel delays as daily commutes were increased by 8-times the ‘normal’ travel time.
8/1/2007 Interstate 35W Minneapolis, Minnesota (Minneapolis Interstate, n.d.)	Collapse The bridge had been classified as structurally deficient and fracture critical as it was aging and in need of repair. The bridge failed during evening rush hour because of inadequate load capacity due to a design error. As a result of gusset plate failure, 13 people died and 145 were injured.	Closure duration: 14 months. There were significant traffic impacts as the bridge serviced roughly 140,000 vehicles per day. On an accelerated schedule, the replacement bridge was designed and constructed an opened on 9/18/2008.
5/23/2013 Interstate 5 Washington (Oullette, 2016 and Jansen, 2014)	Collapse An oversized trailer clipped a cross beam while driving across the bridge which resulted in a catastrophic failure. The bridge was ‘fracture critical.’ Two cars fell into the Skagit River, injuring 3 (no fatalities present).	Closure duration: 14 months. The bridge was a major artery and serviced 71,00 vehicles per day between Vancouver, British Columbia, and Seattle. The bridge was rebuilt to accommodate larger heights with an 18-foot clearance in all lanes.
3/15/2018 Florida International University Miami, Florida (partial collapse) (National Transportation Safety Board, 2018).	Partial collapse A partially constructed 174-foot pedestrian bridge experienced nodal connection failure between the bridge deck and two truss members. To keep traffic flowing, the parties involved in the project deemed it was safe for traffic to remain operational during construction, neglecting that the bridge had multiple cracks which continuously grew. As a result of this negligence, the bridge fell 18.5 feet onto SW 8th Street injuring 10 and killing 6.	Closure duration: 9 days. SW 8th Street, an 8-lane roadway, was closed between 107th and 117th Avenue (10 blocks). The roadway that serviced 68,7262 vehicles per day, was closed for 9 days while crews removed the debris from the scene and investigated the cause of failure.

CASE STUDY EXAMPLES

The case studies in this section were selected because they illustrate multi-objective, multi-asset, multi-modal, and multi-attribute tradeoffs to serve as a connection between planning, construction, repair, and rehabilitation. This thesis primarily focuses on the multi-modal and multi-attribute tradeoffs which consist of user shifts, agency plans and innovative construction. In a broad sense, multi-modal and multi-attribute tradeoffs are used to describe road user preference when conditions are both certain and uncertain, highlighting road user activity and occurrence. This provides a connection between the decision making of agency officials which leads to effective planning while ensuring projects stay on budget and are completed on time.

The case studies were also selected because they produce variations in the type of project and scope of project. The CTA Green Line focuses on a specific line of rail (giving perspective from an alternate mode of transportation. The I-710 case study focuses on a freeway segment with high traffic volumes and has an emphasis on overall pavement condition. The I-495 case study incorporates tradeoffs from both I-710 and the Green Line to give a larger picture of the decisions and tradeoffs made during an emergency bridge closure. By providing these variations, the audience can better understand the greater picture: there are inevitable multi-modal and multi-attribute tradeoffs in every transportation repair and rehabilitation project.

Case of CTA Green Line Rail Repair/Rehabilitation

The repair and rehabilitation of the Chicago Transit Authority (CTA) Green Line (formerly known as the Lake Street L) rail demonstrated user shifts and agency plan tradeoffs. Throughout the project line closures led to an increase in travel time and major delays. This subsection reviews the timeline of the project and the experiences.

In January 1994, the CTA decided to suspend all operations of the Green Line for two years (until 1996) due to worsening infrastructure as well as decreased ridership, increased unemployment and urban sprawl, and financial losses. In 1983, the Green Line serviced 68,650 weekday riders. Leading up to the closure (in 1993), the Green Line serviced 26,800 riders per weekday across 27 stations. In other words, in this 10-year timeframe (from 1983-1993), the CTA Green Line experienced a 61 percent decline in ridership (Abrams, 1998). Figure 2-1 below is a timeline of the events contributing to the CTA Green Line project.

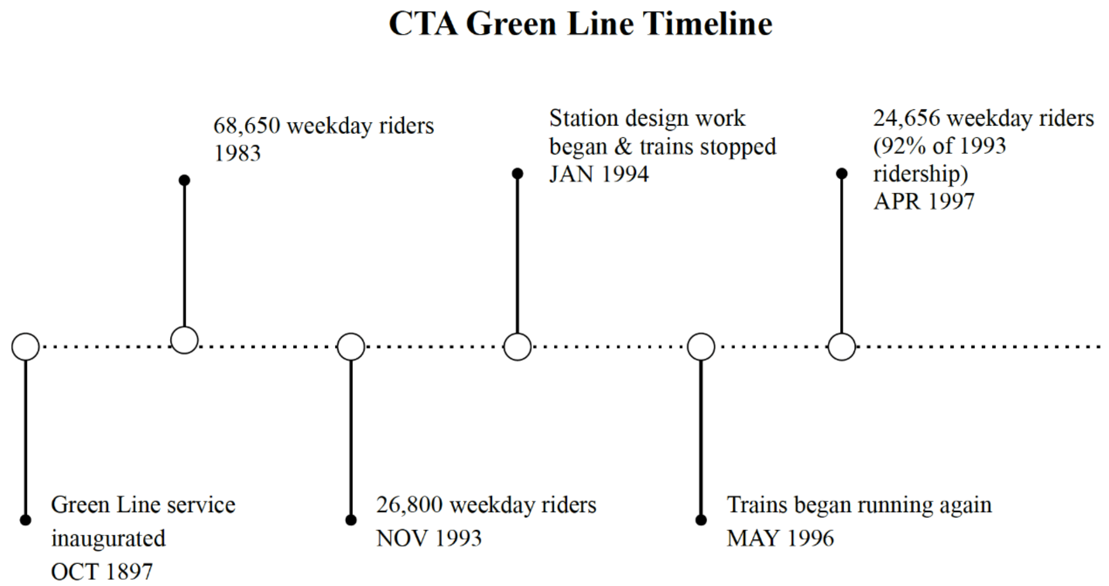

Figure 2-1 CTA Green Line Timeline (Abrams, 1998)

In 1994, the Green Line extended for approximately 21 miles from Oak Park and the West Side, through the Loop (a business and community area), and into the South Side and West Englewood ("Green Line (CTA)", 2020). Sections of the rail date back to 1893, hence the need for major rail rehabilitation. The majority of the wear and tear on the Green Line was caused by trains carrying heavyweight cars degrading the steel spans. As a result, unnecessarily long slow zones were implemented as column base footings began failing. Although spot repairs were ordered, the Green Line had already surpassed its life expectancy as ties and rails were also needed at various locations along the track. Needless to say, these major deficiencies created increased speed reductions across long segments of track, thus significantly increasing the line's running time (Abrams, 1998).

The increased number and length of slow zones resulted in a decrease in ridership which precipitated the CTA's plan to suspend the line. As a multi-modal alternative (a user shift), the CTA urged riders to catch the Blue Line (formerly known as the Congress Line). The downside to this is that the Congress Line was about a mile away from the current Lake Street L and would force riders to use supplemental bus service to reach the station ("Saving the Green Line", 2015). The CTA created the No. 23 Washington Express bus which ran parallel to the Green Line but in an effort to decrease travel time, the route had limited stops. The CTA also utilized the No. 38 Michigan Express bus which also had expedited travel time and fewer stops. In summary, the CTA planned to suspend the 21-mile, 30 station Green Line and replace it with the Blue Line, which was located a mile away. To accommodate the gaps between lines, the CTA provided buses. An average train ride was about 36 minutes with access to all 30 stations. The alternate bus ride was on average 22-30 minutes long with limited access to stations which forced users to walk farther distances to make up for the limited stations. This presented a major inconvenience to the CTA riders and ultimately lead to a 60% decrease in ridership from 1988-1993 (Abrams, 1998).

Although the CTA had plans to permanently suspend the Green Line, there was a shift in agency plans due to public resistance from the Lake Street 'L' Coalition (a group of Chicago residents who were in support of the Green Line). The Coalition partnered with the Neighborhood Capital Budget Group and campaigned to keep the line operational while devising a plan to improve safety, increase pedestrian access, increase jobs and employment, and rebuild the economy. The Coalition's plan was a success as ten days after the campaign launched, the CTA announced a $300 million proposal to rebuild the Green Line. The CTA proposed to rebuild the Green Line while incorporating the Coalition's ideas for community and economic development as well as mixed-use transit centers ("Saving the Green Line", 2015)

The project duration was from January 1994 to May 1996 (approximately 2 years). There were 27 stations within the Lake Street L and 3 stations within the loop. The plan was to rebuild all 27 stations however the entire project budget would have been consumed without addressing the structural issues, which is crucial to returning the rail line to its functional operation. With the $300 million budget, the CTA needed to manage funding accordingly and prioritize stations that needed the most work. The plan was to create a larger gap between stations, producing less frequent stops, decreasing service time and ultimately increase ridership (Abrams, 1998). The scope of the project was limited due to financial challenges. The CTA needed to find a balance between the construction economy and rider accommodation which resulted in some stations receiving small improvements such as basic refurbishing while other stations were completely rebuilt.

There were varying opinions when determining the new station route of the Green Line. "There are too many stations. Some of these stations are within two blocks of each other. That's not a rapid transit system, that's a cab", said the CTA President Belcaster (Chicago "L".org: History). "Some of our young people can't get around without the stops in their community. They'll have to cross through gang territory. We're just not going to take it", said Senator Rickey Hendon (Chicago "L".org: History). Ultimately to accommodate its riders, the CTA devised a plan to repair, completely reconstruct, and even eliminate some stations. The design of some stations consisted of supplying full accessibility via the installation of elevators and ramps. Minor improvements consisted of new paint coats and improved and increased signage and lighting. On the structural side, all column base footings and bridges were replaced in addition to the replacement or renewal of signal and traction power systems. Regarding rider accommodation, the Green Line consists of fewer stations, resulting in less frequent stops, meaning running times have been improved.

After conducting an interview with a current CTA employee, it was determined that at the time of closure, the Green Line consisted of 33 total stations: 27 stations servicing Green Line trains and 6 shared stations servicing the Green Line and other CTA lines. After reopening in May of 1996, the Green Line consisted of 22 stations, with plans for a 23rd station the following year (Hautzinger, 2020). As shown in Table 2-2 below, eight stations were totally rebuilt and six stations received improved entrances, upgraded ramps, and elevators. An additional five stations received refurbished platforms, light rehabilitation, new paint, and improved signage. Three stations were renewed and only one station received an entrance rebuild (Abrams, 1998). This was the sum of the 23 stations at the time of reopening in 1996. Overall, there were a total of 6 stations that were completely eliminated primarily due to their close proximity to other stations and low ridership. Today, the Green Line consists of 30 stations (Abrams, 1998, Hautzinger, 2020).

Table 2-2 CTA Green Line Station Renovation (Abrams, 1998)

Action	# of stations
Totally rebuilt stations	8
Improved entrances & upgraded ramps & elevators	6
Refurbished platforms, light rehabilitation, new paint, & improved signage	5
Renewed stations	3
Entrance rebuild	1
Total stations as of 1998	23

In summary, after the completion of the Green Line repair and rehabilitation project, ridership increased 92% percent. Prior to construction, both the rail ridership and infrastructure were deteriorating. With the help of the Lake Street L Coalition, the CTA was able to balance rider accommodation and financial impact. Not only does this have a positive impact on service and overall infrastructure quality, it also incorporated decreased delay time and encouraged multi-modal alternatives. Additionally, the CTA also announced a computer hardware Maintenance Management System in an effort to reduce costs and improve efficiency. According to the Chicago Transit Board Chairman, “Investing in maintenance technology improved operation efficiency, lowers maintenance costs and ultimately improves the service provided to our customers. These efficiency improvements help to use our limited resources more effectively, which benefits our bottom line. All of these relate to providing the best service possible for our customers” (“New Maintenance Management”, 2005). To date, the CTA has a total of 1,864 buses that operate on 129 routes, servicing 10,768 stops and 1,492 train cars that operate on eight routes, serving 145 stations (“CTA Facts at a Glance”, 2017). With the creation of the 2005 Maintenance Management System, the CTA now has the technology and resources to prevent major rehabilitation issues in the foreseeable future.

Case of I-710 Long Beach Freeway Accelerated Rehabilitation

The I-710 Long Beach Freeway accelerated rehabilitation project presented tradeoffs in innovative construction with 55-hour weekend closures over the duration of eight weeks (for the main rehabilitation portion of the project). Servicing 164,000 vehicles per day with 13% of the of the vehicles being heavy vehicles (trucks), I-710’s deteriorated concrete pavements exhibited cracking and faulting (“Rapid Pavement Rehabilitation”, 2014). This section of I-710 was nearly 50 years old (and had never received any major rehabilitation) and consists of 4.4 centerline-kilometers, totaling 26.4 lane-kilometers (Lee, Lee, & Harvey, 2006). The site was selected for rehabilitation using the Long-Life Pavement Rehabilitation Strategies (LLPRS) program with a goal “to rebuild approximately 2,800 lane-km of deteriorated freeway of the total of 78,000 lane-km within the California state highway system (“Rapid Pavement Rehabilitation”, 2014). Highways with a 150,000 vehicle per day ADT or 15,000 truck ADT were given the utmost attention ultimately prioritizing the I-710 Long Beach Freeway. The need for highway rehabilitation became necessary as both traffic demand and the number of heavy vehicles (accessing the Port of Long Beach) continued to increase. Not only was rider quality impacted, safety, vehicle operation, highway maintenance costs, and delays were also impacted.

This project was unique as the main rehabilitation was completed in just 8 weeks with the 55-hour closures weekends. An incentive was awarded to the contractor if they completed the main rehabilitation in less than 10 weekend closures. The amount awarded was $100,000 per weekend. However, if the contactor did not complete the main rehabilitation within 10 weeks (if the contractor required more time), they were subject to a $100,000 penalty (Lee, Lee & Harvey, 2006). Work began in April 2001 with a starting contractor cost of $16.7 million. The contractor completed the main rehabilitation work in June 2003 hence why this project is known as the 55-hour rehabilitation project. By the end of the project, the contractor cost increased to approximately $20 million due to unexpected problems during construction. These problems included "hazardous asbestos in the median, roadway alignment discrepancies between the plan and actual surveys, and delay in finalizing AC mix binder contents" (Lee, Lee & Harvey, 2006). Luckily these unexpected problems did not create any user delays.

If the California Department of Transportation (Caltrans) decided to do a partial or full lane closure during the weekday, 5,400 vehicles per hour would be impacted. If the closure were to occur during the weekend, only 4,300 vehicles per hour would have been impacted which is slightly less than the weekday impact. With that said, Caltrans determined weekend closures were best as it impacted less vehicles per hour. Additionally, there is a stereotype that night construction is 'better' than weekend construction as it produces less of a traffic delay. Again, this was not the case of the I-710 rehabilitation project. Night construction typically consists of 7-hour to 10-hour closure periods and would have increased the risk of efficiency while handling large volumes of materials. During these short-term overnight periods, only short-term pavement with a 10-15-year life expectancy can be constructed. However, using the LLPRS program and software, Caltrans determined that a 30-year life expectancy could be achieved via weekend construction with longer working periods (55 hours) (Lee, Lee & Harvey, 2006). Not only did this accelerated rehabilitation process increase the life expectancy of the freeway section, it also ensured better surface conditions, ultimately increasing rider quality.

In summary, due to Caltrans' efforts to inform the public, there was significantly lower traffic demand during the construction phase which resulted in a user delay reduction. Caltrans increased their communication by posting messages on local roadways, used changeable message signs and detour signs, updated their website frequently, and utilized social media. There were no apparent congestion concerns as traffic continued to operate at a free-flowing speed while traveling on I-710 and along the nearby, surrounding roadways. In fact, the peak hour traffic was decreased by 37% while the ADT decreased by 39% ("Rapid Pavement Rehabilitation", 2014). Although there was initial concern of travelers avoiding I-710's construction area, it appears there was a learning curve. During the first weekend of construction, vehicles avoided the area. However, traffic began to increase on the following weekends as there were no apparent delays or user shifts in time. Overall, the I-710 Long Beach Freeway accelerated rehabilitation project was a success as it showcased the balance between timely (and quality) construction while also prioritizing safety, accommodating riders, and decreased overall travel delay.

Case of I-495 Bridge Closure, Wilmington, Delaware

The case of I-495 was selected because it is an interesting and unique "unplanned" emergency repair and rehabilitation project. Additionally, the location of the site is in the backyard of the University of Delaware, approximately 20 minutes from the main campus. This particular project has a variety of contributing factors all of which related to the thousands of daily road users. Now more than ever, construction is inevitable, thus impacting the everyday lives of road users and transit commuters. In a matter of weeks, the I-495 bridge went from being a safe and stable structure (passing inspection) to an unstable and unsafe structure, failing inspection and requiring immediate repair. The bridge was repaired in two months. This project stands out due to the fast response on behalf of the Delaware Department of Transportation and its efforts to restore a bridge that carries 90,000 vehicles per day in a construction period of approximately sixty days.

The case of I-495 was selected as the primary focus for this thesis because of the unique multi-modal, multi-attribute, multi-objective, and multi-asset tradeoffs presented as a result of the emergency closure. Because these tradeoffs often overlap and conflict one another, decisions made on behalf of the Delaware Department of Transportation because a major focus. How did DelDOT consider these tradeoffs, their attributes, and impacts to determine how to proceed with the emergency construction of Bridge 1-813.

There's a plethora of tradeoffs for state agencies to consider as any decision will impact user shifts, agency plans and innovative construction. This case study is developed more thoroughly in Chapter 3.

SYNTHESIS

As mentioned in Chapter 1, the objective of this case study is to educate stakeholders about the decisions made surrounding multi-modal tradeoffs. The I-710 Freeway emphasized the importance of innovative construction through a monetary contractor incentive while also having minimal impacts to road users. The CTA Green Line repair and rehabilitation project taught the importance of balancing budget with user accommodation as these decisions will impact both operational use and overall ridership. It also stresses the importance of engaging a community of stakeholders and incorporating their feedback into decision making. The CTA also took the extra step to recognize that access to multi-modal transport was also a consideration when determining improvements to the line; they must provide system users with other transit uses during the construction period. Lastly, the I-495 bridge closure examines how a decision made by a single contributor can severely impact thousands whether that be an alternative route or mode of transportation. While planned construction projects have extensive background and require vigorous thought and considerations, unplanned constructions projects require the same and if not more. A key aspect in all case studies resented in this section is that planning, coordination, and communication is key. Overall, the audience is able to understand that there are inevitable multi-modal and multi-attribute tradeoffs in every transportation repair and rehabilitation project.

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CHAPTER 3

Control, Monitor, and Inform: Lessons Learned from the 2014 Delaware I-495 Emergency Bridge Closure

ABSTRACT

The 2014 I-495 emergency bridge closure in Wilmington, Delaware serves as an example of innovative practices that are relevant to future transportation repair and rehabilitation projects, both for emergency bridge or road closures (unplanned construction projects) and scheduled bridge or road closures (planned construction projects). The closure of Bridge 1-813 over the Christina River required a complex bridge repair and resulted in travel disruptions for the 90,000 users per day. The project demonstrated the value of communication, teamwork, effective planning, real-time traffic data, emergency contracting authority, and system redundancy. This in-depth case study provides an overview of the I-495 bridge closure, examines why the closure is of interest and how complex decisions were made by the Delaware Department of Transportation (DelDOT), and highlights the innovative strategies used to facilitate reopening the bridge and tradeoffs made by the decision-makers, contractors, and road users to mitigate the impacts on road users. The lessons learned from the bridge closure with respect to traffic control, traffic monitoring, and informing road users are identified.

INTRODUCTION

The availability and condition of transportation infrastructure plays an important role on the everyday life of road users, impacting accessibility and reliability. It also has secondary impacts on businesses and other modes of transportation. While every emergency repair or major rehabilitation is unique in terms of the nature of the improvement and the disruptions caused, there is an opportunity to learn from past experiences.

At 6pm, June 2, 2014, Delaware Department of Transportation (DelDOT) closed the 37-span bridge (identified as Bridge 1-813) on Interstate 495 (I-495) crossing the Christina River in Wilmington, Delaware due to unexpected and unsafe tilting of the piers. As Bridge 1-813 typically serviced nearly 90,000 vehicles per day, the emergency closure marked for the public, the beginning of a complex decision-making process aimed at mitigating the impact of the bridge closure on road users. This decision-making process considered the impacts of the immediate closure, the impacts during the bridge repair and strategies to ensure the longer-term serviceability. Southbound I-495 was open to traffic on July 31, 2014 and northbound I-495 was open to traffic on August 23, 2014, less than three months after the initial closure.

This chapter presents a case study documenting the bridge closure and repair. The case study is used to identify the lessons learned that are relevant to executing a major transportation facility repair or renewal that involves significant disruptions due to either preplanned or emergency closure.

Objective and Intended Audience

The objective of this chapter is to identify and discuss the lessons learned surrounding the I-495 emergency bridge closure in Wilmington, DE. The complexity of the tradeoffs surrounding the bridge closure, the decision-making process, and information sharing influenced the strategies employed and the timeline. The insights can serve as a guide for future transportation repair and rehabilitation projects (planned and unplanned). This chapter is specifically intended for key stakeholders in project planning, maintenance, mitigation, management, operations, construction, and even funding, such as city officials and politicians (sponsors), federal and state planning and transportation agencies, and private and public consultant engineering firms. Overall, the closure of Bridge 1-813 over the Christina River emphasized the value of communication, teamwork, effective planning, real-time traffic data, emergency contracting authority, and system redundancy.

Background

The emergency closure of Bridge 1-813 resulted in a plethora of travel impacts and engaged dozens of consultants and contractors. The reasons behind the closure and timeline provide some context for the strategies developed and actions taken.

A 45,000 metric ton (50,000 ton) stockpile of dirt was stored adjacent to the bridge piles by a third party. The stockpile created lateral subsurface pressure on the bridge piles, ultimately causing the structure to be deemed "unsafe for the traffic volume that normally crosses the bridge" (McNeil et al., 2019). Once the problem was identified DelDOT announced the immediate closure of the 40-year-old, 1,463 meter (4,800-foot) bridge with 37 spans (two main spans crossing the river and 35 approach spans) (O'Shea, 2015). Figure 3-1 maps the location of Bridge 1-813 with respect to interstates I-95 and I-495 in Delaware, and the key exits along I-495 with an emphasis on the 'final' exits prior to the closure in both the northbound and southbound directions. The interstate was closed between Exit 2 and Exit 3 in both directions as Bridge 1-813 was located between these two exits. Figure 3-2 shows the area in the vicinity of Bridge 1-813 and

Figure 3-3 is an image of Bridge 1-813.

Four initial reports of a problem with Bridge 1-813 were made before the bridge was closed on June 2nd. The first was from a civilian in April 2014 regarding median wall misalignment. The second was from an engineer in May 2014 regarding tilting of the support columns. The third was from another civilian in May 2014 regarding sunken spans. The fourth was from a street sweeper in June 2014 regarding concerns with the barrier wall. Finally, in June 2014, DelDOT sent the Assistant Director of Bridges and Structures and a bridge inspection engineer to the site and the bridge was deemed structurally unsafe. The bridge was closed on June 2, 2014 at 6 p.m. and all traffic was directed off the bridge by 9 p.m. (Delaware Department of Transportation, 2014).

After closure, inspection determined that a total of eight of the thirty-seven columns were affected: four were tilted and out of vertical alignment by as much as 4% and required replacement while another four columns needed to be repaired in plane (1). The piers were tilted to the southwest, and the northbound bridge superstructure was 45 cm (18 inches) lower and separated 7.5 cm (3 inches) from the southbound superstructure (2). Additionally, at some locations, the underground piles, which were designed to extend 30.5 cm (12 inches) into the footer, were no longer attached. Figure 3-4 shows the conditions at the time of closure.

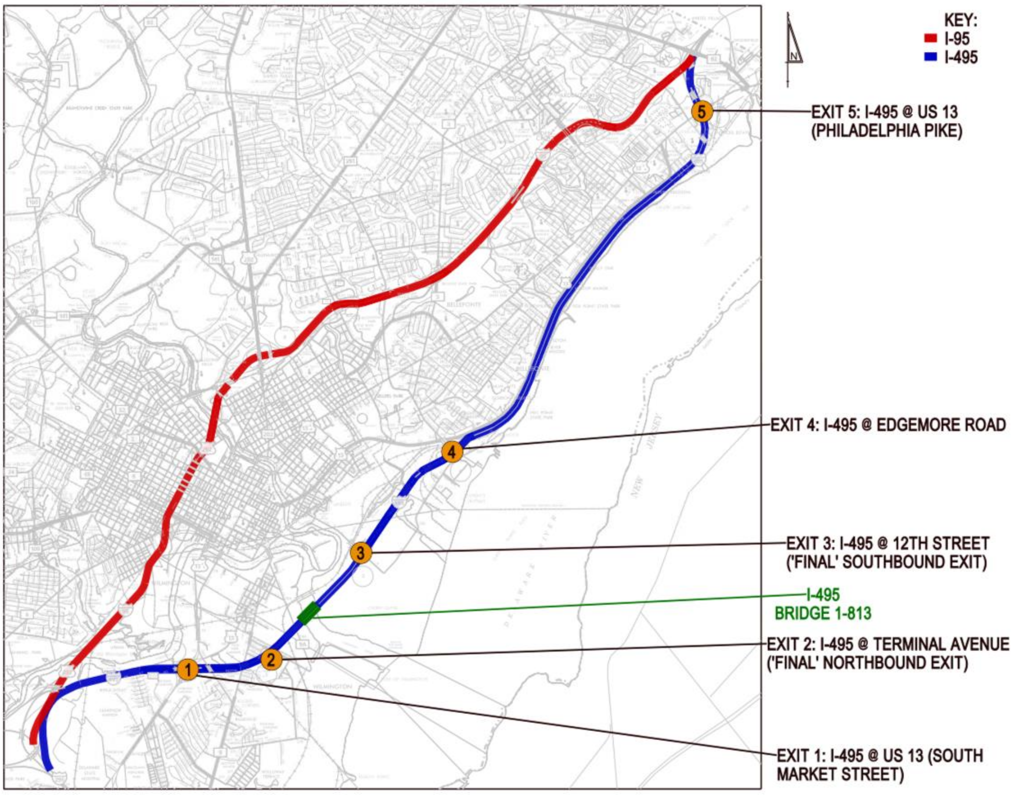

Figure 3-1 Project Limits of the I-495 Emergency Closure

Figure 3-2 Google Earth View of the I-495 Bridge 1-813

Figure 3-3 Image of the I-495 Bridge 1-813 (Benton, 2014)

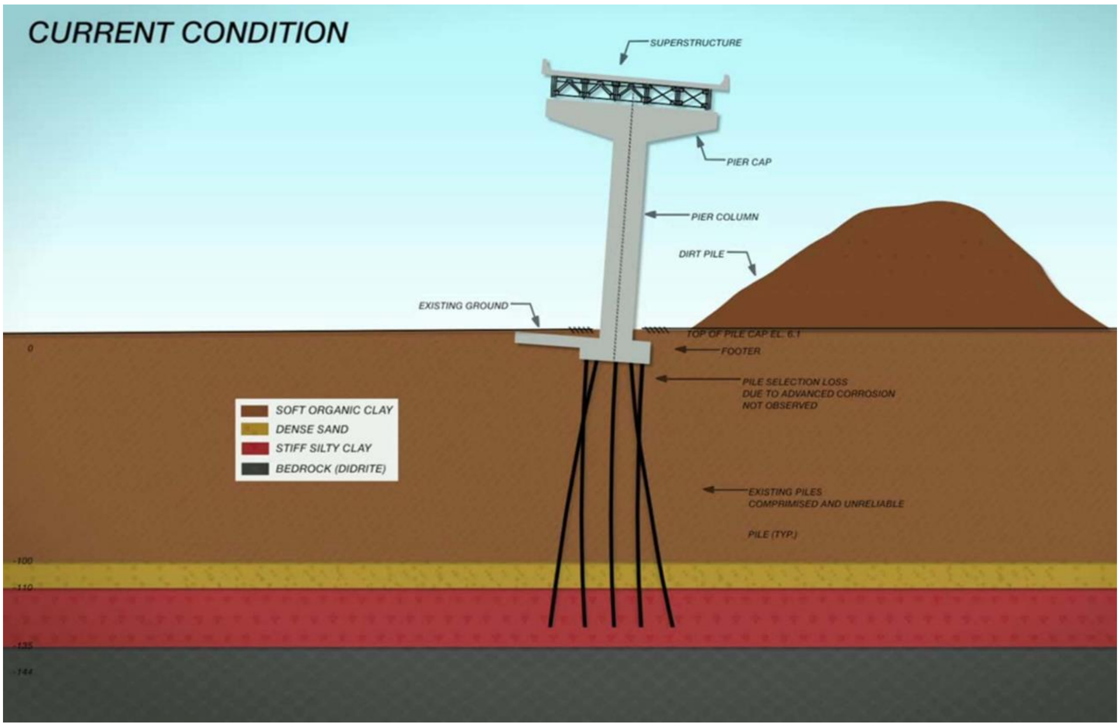

Figure 3-4 Condition of Piers Prior to Repair (Benton, 2014)

Since the closure of Bridge 1-813 was an unplanned construction project, DelDOT had to recognize the situation, develop a strategy, and engage contractors and consultants expeditiously including accessing resources including nearby state agencies, and police departments. DelDOT had to quickly consider its range of options (people and resources) available and brainstorm alternative structural solutions. Just three days after the closure, DelDOT's Bridge and Structures, and Construction sections, AECOM, the Federal Highway Administration (FHWA), the University of Delaware, JD Eckman, and HNTB had established the scope of repairs. As the project progressed, DelDOT quickly realized the scope of repair required modification of both the temporary and permanent construction plans to accommodate issues that emerged.

In summary, the closure of Bridge 1-813 was a result of the unauthorized stockpiling of dirt adjacent to the bridge and four overlooked civilian reports. Additionally, the design of the bridge using slender H piles was vulnerable to lateral movement, which resulted in over a 1.2 m (4-foot) settlement.

DelDOT, its contractor and subcontractors worked around the clock to remove the dirt stockpile and ensure contaminated soil and groundwater were property treated. Construction was split into two phases as DelDOT had to consider different tradeoffs that recognized user shifts, agency plans, and innovative construction methods, which resulted in a complex decision-making environment. DelDOT utilized existing plans and reports to assist with this decision-making process. Finally, DelDOT's efforts to control, monitor, and inform road users of the changes along I-495, I-95 and on nearby impacted routes was key to making this project a success.

Methods

The exploratory case study methodology used in this research focuses on answering "what" and "who" questions surrounding the I-495 emergency bridge closure (Yin, 2014). The case study is developed based on the review of reports, presentations, and websites (grey literature) that are documented throughout the chapter. Eight semi-structured interviews with transportation and bridge engineers and planners supplement the material published in the grey literature. An assessment of the impacts of the closure on road users is based on in-depth analysis of traffic flows before and during the closure that provides insights into the changes in traffic patterns. A more detailed exposition of the methodology and case study are available in Withers (2021).

Themes emerging from the case study are used to identify lessons learned in terms of user shifts, agency plans and innovative construction methods, the different time frames (immediate closure, during repair and long-term serviceability), and the concepts of control, monitor and inform. User shifts refer to the shift in time-of-day travel, the impact and usage of alternative routes and modes, and the usage of multiple modes of transit. Agency plans refer to improvements to alternative routes and enhancements to alternative modes. Innovative construction refers to scheduling and overall project timing. The different time frames refer to DelDOT's actions taken during the immediate closure (right after the bridge was closed), during the three-month repair, and long-term serviceability which occurs after the bridge is reopened. The concepts to control, monitor, and inform traffic were used to get I-495 reopened as soon as possible while also ensuring the long-term serviceability.

Outline of the Chapter

This chapter is organized into five key sections: the introduction (this section), literature review, the case study, lessons learned, and conclusion. The chapter is structured to introduce the topic, state the objective, give background about the case study, and describe methods for completing this study. Then, the chapter discusses similar and relevant literature such as why the case is of interest, and existing plans and resources. Next, the chapter discusses the engineering problem at hand, how DelDOT worked to solve the problem, and how traffic (road users) was impacted. Then the chapter examines the lessons learned and how it related to the decisions made during the bridge closure, which ultimately led to project success. Last, the conclusion includes a summary and presents key findings.

LITERATURE REVIEW

The literature review is organized around two topics: why the case of the I-495 emergency bridge closure is of interest; and a summary review of the existing plans and reports DelDOT referenced to assist with the decision-making process.

Why Is This Case of Interest?

An interesting aspect of the I-495 emergency bridge closure that makes it unique is the fact that Bridge 1-813's structural deficiency was not a result of a common cause of bridge failures. Design and structural deficiencies, construction defects, accidental overload, poor material quality, and poor maintenance are the most common causes of bridge failures. Extreme events including extreme loads, blasts, fires, and natural disasters are also common causes of bridge failures (Wardhana and Hadipriono, 2003). Bridge closure due to a dirt stockpile causing lateral movement of the bridge substructure is unprecedented.

Wardhana and Hadipriono's (2003) analysis of bridge failures in the United States between 1989 and 2000 also determined that eight out of the 503 bridge failures occurred during the construction phase, 386 during service, and the timing is unknown for 109 bridges. Out of the bridges that failed during service, 17 failures were due to distresses, 80 resulted in partial closures, 12 in total collapses, and 277 were unknown (Wardhana and Hadipriono, 2003). Relating this data to the I-495 bridge closure, Bridge 1-813 experienced failure during service, which primarily resulted in distresses caused by the tilting of columns and piers, but with no collapse or loss of human life. However, other bridges (and road users) were not so lucky.

Table 3-1 summarizes just a few bridge failures within the United States from 2001 to 2018, providing a date and location of occurrence, description of the bridge failure, and the impact the failure had on traffic.

The case of the I-495 emergency bridge closure is of interest because DelDOT had to consider different strategies considering user shifts, agency plans, and innovative construction methods, which resulted in a complex decision-making. Imbedded within these strategies are multi-modal, multi-attribute, multi-objective, and multi-asset tradeoffs that are common to many emergency closures or planned rehabilitation projects. In the context of this chapter these strategies involve different investments to reduce traffic impacts, construction duration, and project costs. The tradeoffs are among the impacts on travel time, trip disruption, mobility, and access that differ among stakeholders—for example, user shifting between modes or time of day of travel, and investments to improve other assets to reduce disruption. While tradeoffs are addressed in the literature for transportation investments (Sinha and Labi, 2011), rehabilitation projects (Lee et al., 2006), and different asset classes (Bryce et al, 2018), such tradeoffs have not been explicitly documented for emergency repair.

The I-495 case study was selected because it illustrates these tradeoffs and the connection between planning, construction, repair, and rehabilitation. This chapter primarily focuses on the multi-modal and multi-attribute tradeoffs that reflect road user preferences and choices when conditions are both certain and uncertain in response to the decisions made by DelDOT (the asset owner) that are influenced by the available resources, the budget and the time to repair the asset.

In summary, the objective of this study is to provide an analysis of the lessons learned based on the decisions made surrounding the I-495 emergency bridge closure while discussing which attributes ultimately lead to the overall success of the project. The I-495 bridge closure examines how a decision made by DelDOT impact thousands whether that be an alternative route or mode of transportation. For both planned and unplanned repair and construction projects, planning, coordination, and communication are key. The case study demonstrates that there are inevitable multi-modal and multi-attribute tradeoffs in every transportation repair and rehabilitation project.

Existing Plans and Resources

To support the complex decision making needed for the repair, DelDOT utilized existing plans, reports, and tactics. DelDOT implemented the practices discussed in the Transportation Incident and Event Management Plan (TIEMP), which provides a structure for how DelDOT will function in emergency operations (Edwards and Kelcey, 2004). The TIEMP discusses the level of response, area of impact, and resources available while also recognizing the role of Emergency Operation Centers in unplanned events and determines the individual with the highest level of decision-making. To clarify, the TIEMP did not provide a set of plans regarding what to do given the emergency closure of I-495, but instead provided a general understanding of the parties involved, their responsibilities, and how to communicate. In the case of the I-495 emergency bridge closure, DelDOT’s Secretary of Transportation, Shailen Bhatt, possessed the highest level of decision-making before presenting the idea to Governor Jack Markell for final approval.

Table 3-1 Select Bridge Failures in the U.S. from 2001 to 2018

Date/Location	Bridge Failure	Traffic Impacts
9/15/2001 Queen Isabella Causeway South Padre Island, Texas (Tyrrell, 2001)	Partial collapse A 48.8 m (160-feet) section of the Queen Isabella Causeway collapsed after a barge stuck the structure. Twelve hours later another section of the bridge collapsed. As a result, vehicles plummeted into the Laguna Madre, killing 8 and injuring 13.	Closure duration: 2 years. Since the bridge was the only connection from South Padre to the mainland, vehicles were transported across the laguna via boat. There were severe travel delays as daily commutes were increased by 8-times the ‘normal’ travel time.
8/1/2007 Interstate 35W Minneapolis, Minnesota (Minnesota Legislative Reference Library,2020)	Collapse The bridge had been classified as structurally deficient and fracture critical as it was aging and in need of repair. The bridge failed during evening rush hour because of inadequate load capacity due to a design error. As a result of gusset plate failure, 13 people died and 145 were injured.	Closure duration: 14 months. There were significant traffic impacts as the bridge serviced roughly 140,000 vehicles per day. On an accelerated schedule, the replacement bridge was designed and constructed an opened on 9/18/2008.
5/23/2013 Interstate 5 Washington (Stark et al., 2016)	Collapse An oversized trailer clipped a cross beam while driving across the bridge resulting in a catastrophic failure. The bridge’s ‘fracture critical’ design meant that one small crack could trigger more failure. The bridge’s height is listed as 5.4 m (17 feet 9 inches) (at the center) but the bridge curves at the edges measuring 4.4 m (14 feet 5 inches). Two cars fell into the Skagit River, injuring 3 (no fatalities present).	Closure duration: 14 months. The bridge was a major artery and serviced 71,00 vehicles per day between Vancouver, British Columbia, and Seattle. The bridge was rebuilt to accommodate larger heights with an 18-foot clearance in all lanes.
3/15/2018 Florida International University Miami, Florida (National Transportation Safety Board, 2018).	Partial collapse A partially constructed 53 m (174-feet) pedestrian bridge experienced nodal connection failure between the bridge deck and two truss members. To keep traffic flowing, the parties involved in the project deemed it was safe for traffic to remain operational during construction, ignoring growing multiple cracks. As a result of this negligence, the bridge fell 5.6 m (18.5 feet) onto SW 8th Street injuring 10 and killing 6.	Closure duration: 9 days. SW 8th Street, an 8-lane roadway, was closed between 107th and 117th Avenue (10 blocks). The roadway that serviced 68,7262 vehicles per day, was closed for 9 days while crews removed the debris from the scene and investigated the cause of failure.

Bridge 1-813 served nearly 90,000 vehicles per day and it was an utmost priority to reopen the bridge as soon as possible. The southbound direction of travel showed a greater travel impact therefore it was prioritized over the northbound direction of travel. To expedite the construction, the Governor's emergency declaration granted DelDOT emergency procurement authority and DelDOT was able to waive bidding requirements, pull in various agencies and firms, and get to work as soon as possible. Funding from FHWA's Emergency Relief Funds were provided to DelDOT. These funds were utilized to make repairs to the structure. DelDOT was awarded "$30 million for phase I to reopen the bridge and $15 million for phase II to complete permanent repairs to the structure" (Delaware Department of Transportation, 2014). In fact, DelDOT was 100% reimbursed for all phase I temporary repairs during the first 180 days. Additionally, "federal funds for permanent repairs were provided at the normal 90/10 Federal/State interstate share" (2). Also, as DelDOT was not at fault for the closure, DelDOT worked with law firm of Ober Kaler and the Delaware Attorney General's Office to determine how much money was to be recovered by the state.

To assist with the expedited construction process, DelDOT innovatively sourced materials from across the United States. Reinforced steel cages for the drilled shafts were brought from the Governor Mario M. Cuomo Bridge (the replacement for the Tappan Zee Bridge), a major bridge construction project occurring outside New York City. That said, this was an essential purchase and key attribute to the rapid repair of the I-495 bridge. The Governor Mario M. Cuomo Bridge construction had the capacity and flexibility to delay construction a few months to have materials rebuilt while the existing materials were delivered to the I-495 bridge for immediate use. Granted there was a bit of a sizing difference, so the I-495 crew had to size down the cages, but it all worked out in the end and saved months of delay. In fact, the use of materials intended for the New York project reduced the repair time by an estimated 10 to 12 weeks. (2)

Other materials came from across the United States. The drilled shafts also required steel casings which were provided from Oklahoma and Washington while drilling rigs were sourced from New Jersey and Texas. Because the construction area was quite confined and had limited height restrictions, these special rigs were imperative in constructing the 50 m (162 feet) deep drill shafts (2). Overall, DelDOT's ability to maintain communication, utilize its resources, and collaborate amongst engineers and agencies across the United States was a major attribute in the success of the rapid repair of Bridge 1-813.

I-495 EMERGENCY BRIDGE CLOSURE: A CASE STUDY

Solving the Engineering Problem

The engineering problem that resulted in the closure of Bridge 1-813 was the misalignment of eight of the thirty-seven columns, which deemed the bridge unsafe. This was the very first sign that revealed there was an issue with the bridge's superstructure. In typical bridge construction, the adjacent bridge median barriers have a horizontal separation of between 2 and 3 cm (1 inch) and are the same elevation. However, Bridge 1-813's median barriers shifted with a vertical difference of almost 0.45 m (18 inches) and a horizonal separation of roughly 7 to 8 cm (3 inches) (2). In other words, the northbound median was 0.45 m higher than the southbound median making it evident that structural failure had occurred along some points of the bridge. Figure 3-5 shows the 0.45 m difference in elevation between the northbound (higher) and southbound (lower) median barriers.

Bridge 1-813 was closed on June 2, 2014; on June 10, the dirt stockpile was removed and subconsultants began working to drill new foundation shafts. There were two phases of construction: phase 1 ($30 million) to reopen the bridge with temporary repair and phase 2 ($15 million) to complete permanent repairs to the structure (4). Phase 1 consisted of creating "new foundations for piers 12 and 13 and underpinning the foundations of piers 11 and 14, all of which would allow the opening of the bridge" (2). Figure 3-6, a photo taken on-site, shows the temporary support towers and support beams as well as the proposed grade beam at piers 12 and 13 showing the existing piers that will later be demolished after phase 2 of the permanent repairs is completed. Figure 3-7 is an elevation (side) profile drawing of the temporary repairs.

Figure 3-5 Settling Issue Between Northbound & Southbound Median Barriers (Benton, 2014)

Southbound I-495 was open to traffic on July 31, 2014 and northbound I-495 was open to traffic on August 23, 2014. With all temporary repairs completed in both directions, the phase 2 permanent repairs began. The existing piers and columns at piers 12 and 13 were demolished while the columns at piers 11 and 14 remained. Removing the existing columns at piers 12 and 13 without damaging the new temporary support towers and beams presented a challenge so engineers used a wire saw to cut the column into pieces so it could be removed piece by piece. Once the temporary support beam and support towers were completely removed, new concrete pier columns, concrete supports (on top of the grade beams) and pier caps were constructed. “Instead of two hammerhead piers supporting each direction [phase 1], a single pier supported by three columns [phase 2] would carry both directions of I-495” (2). The girder bearings at piers 11 and 14 were also reconstructed. Phase 2’s permanent repairs were completed in April 2015. **Error! Reference source not found.** and Figure 3-9 document the phase 2 permanent foundation repair condition, from both a design perspective and a final project photograph.

Figure 3-6 Proposed Foundation Repair & Temporary Support Elevation (Benton, 2014)

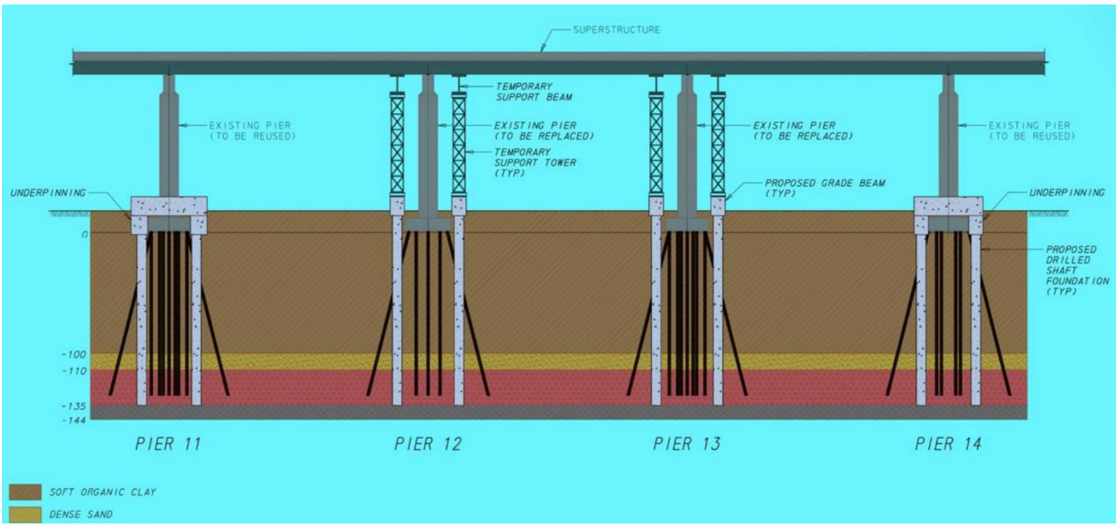

Figure 3-7 Pier 12 and 13 Temporary Support Towers & Support Beams (Source: DelDOT Personnel, with permission)

All construction efforts were led by DelDOT's Assistant Director of Bridges and Structures, Barry Benton and Assistant Director of Construction, Javier Torrijos. Additionally, DelDOT's Chief Traffic Engineer, Mark Luszcz made the decision to prioritize the opening of southbound I-495 from a traffic management standpoint as southbound traffic presented a greater travel impact than northbound traffic. After all phase 1 repairs were made to southbound I-495, DelDOT "completed a road test by running loaded dump trucks across the bridge and braking over the repaired area" (2). The test was successful and after southbound was open to traffic, the remaining focus was placed on the completion of northbound traffic. Table 3-2 outlines the completion dates for temporary phase 1 schedule of I-495.

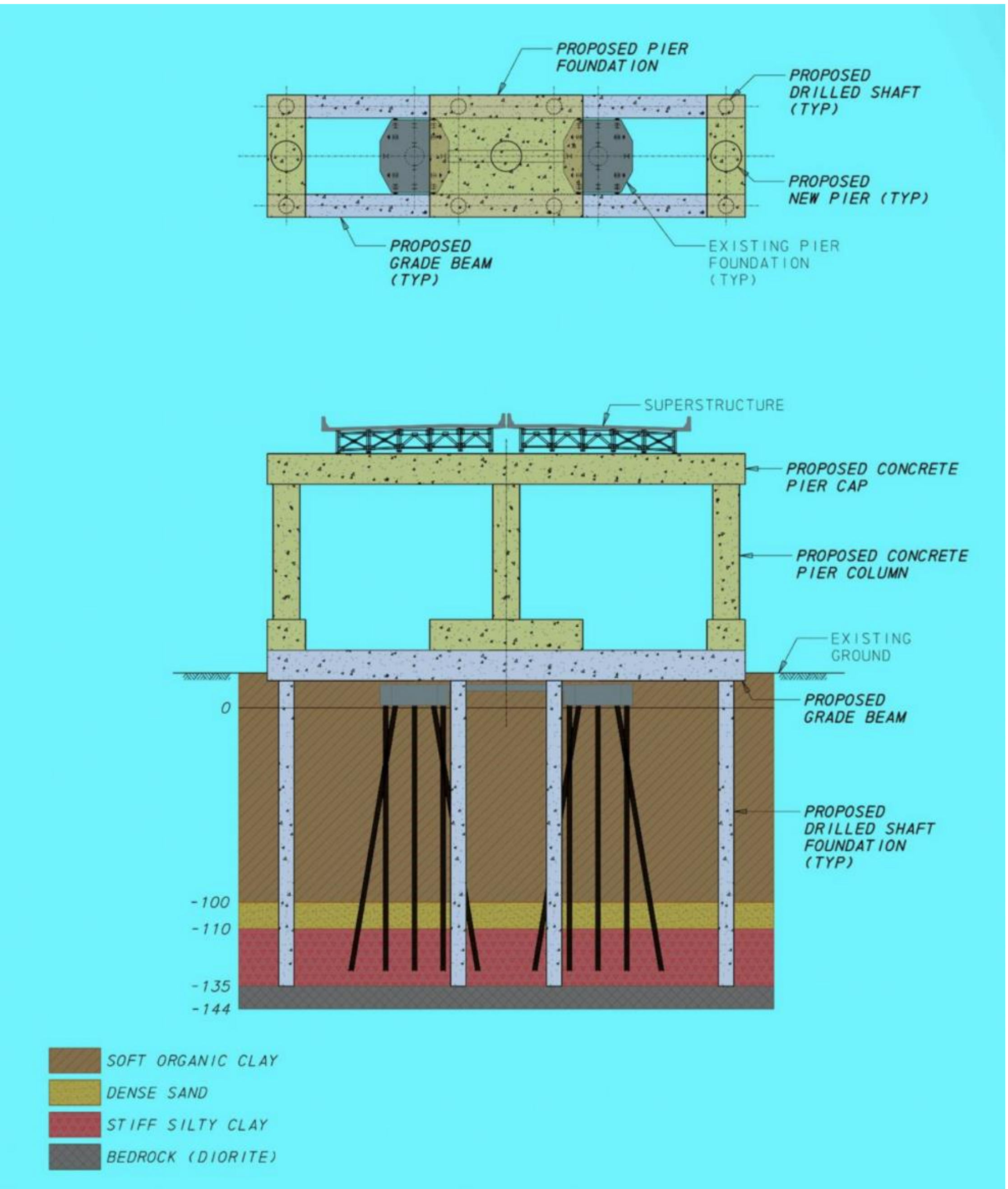

Figure 3-8 Permanent Foundation Repair Condition (Benton, 2014)

Table 3-2 I-495 Temporary Phase 1 Schedule (O'Shea, 2015)

Repair Action	Southbound Completion	Northbound Completion
Drilled shafts began on 6/13/2014	7/16/2014	7/16/2014
Underpinning	7/8/2014	7/25/2014
Concrete grade beams	7/8/2014	7/25/2014
Temporary jacking tower erected	7/22/2014	8/5/2014
Jacking operations	7/29/2014	8/20/2014
Open to traffic	7/31/2014	8/23/2014

Figure 3-9 Permanent Completed Repairs (Benton, 2014)

Analysis of Traffic Impacts

The immediate closure of Bridge 1-813 disrupted traffic throughout the region, inconvenienced users and imposed additional traffic on the alternative routes, adding travel time for non-users. DelDOT reported that during the bridge closure there were peak hour delays of up to 45 minutes, which were observed in both directions along I-95, the most direct alternative route. Delays were monitored using emergency response unit reports, as well as automated detection equipment. There were significant delays during the morning peak period from 7:00 a.m. to 9:00 a.m. and during the evening peak period between 3:00 p.m. and 7:00 p.m. During the weekend, there were 10-15-minute delays observed between the hours of 12:00 p.m. and 7:00 p.m. The traffic on I-495 fluctuates. Typical volumes on I-495 are 90,000 vehicles per day. However, in the days leading up to the closure, an average of 72,000 vehicles per day were observed. During the initial days of the closure (June 2-4, 2014), there was an average of 13,000 vehicles per day using I-495. This is an average reduction of 59,0000 vehicles per day. On the other hand, along I-95, volumes increased by 33,000 vehicles per day, and I-295 volumes increased by 4,000 vehicles per day (Delaware Department of Transportation, 2014b).

Additional road user costs associated with the I-495 emergency bridge closure are significant (Whitman, Requardt & Associates, 2014). User costs associated with the increases in volume along I-95 and I-295 amount to $120,000 per day. Approximately 22,000 daily trips were unaccounted for in this analysis, and further analysis of the usage of local alternate routes, suggests that the remaining 22,000 vehicles utilized SR 2, SR 4, and US 13 (instead of I-95, I-495, and/or I-295). The additional delay cost associated with the local alternative routes is estimated to be $75,00 per day (Whitman, Requardt & Associates, 2014).

Additional analysis of Wavetronix data obtained from the DelDOT Transportation Management Center for I-95 (the primary alternate route) and other alternative routes within the City of Wilmington verifies the increases in usage along I-95 and nearby routes as road users were directed off and away from I-495 (Withers, 2021). Levels of service range from A through F along I-95 for both midweek (Tuesday, Wednesday, and Thursday) and weekend (Saturday to Sunday) morning and evening peak hours. The actual peak hours of traffic also fluctuated both by location and day. The analysis indicates that road users shifted their time-of-day travel to earlier during the closure. Nearby routes also experienced increases in volume from two to thirty six percent primarily along the suggested alternate routes of SR 2, SR 4, and US 13. There was also an increase in traffic over the Delaware Memorial Bridge, suggesting the road users opted to travel through New Jersey instead of traveling through the congested area of I-95 and the City of Wilmington detour routes.

Last, SEPTA and DART data also suggests that road users opted for an alternate mode of transportation to avoid traveling directly through the area of the bridge closure (Withers, 2021). During the month of June, SEPTA rail ridership increased nearly 7% from May to June and 8% from June to July. Rail ridership then decreased 7% from July to August which is also the same time that southbound I-495 was reopened to through traffic. DART bus ridership decreased 1% from May 2014 to June 2014, increased 5% from June to July, and then increased almost 1% again from July to August. No specific evidence was provided to link the fluctuations in SEPTA and DART ridership to the I-495 closure, however it can be inferred there is a relationship between ridership increase due to roadway congestion.

LESSONS LEARNED

The lessons learned focus on traffic control, traffic monitoring, and informing road users. These themes align with DelDOT's Transportation Management Center's (TMC) goal to control, monitor, and inform road users of Delaware's transportation infrastructure.

Traffic Control

Traffic control refers to DelDOT's ability to control the flow of traffic along Delaware's roadways. The lessons learned regarding traffic control are the value of effective planning, the role of emergency contracting authority, and the importance of system redundancy:

- Effective planning – From an organizational and planning perspective, DelDOT utilized its Transportation Incident & Event Management Plan, to provide a structure for how DelDOT as an agency will function in the emergency bridge operation. Prior to the closure, DelDOT understood the level of response needed, potential area of impact, resources available, and the existing hierarchal chain of command.
- Emergency contracting authority – The granting of emergency contracting authority by the Secretary of Transportation and the Governor meant that the need for bids was waived, and consultants and contracts engaged without any delay. To ensure the safety of road users, DelDOT also coordinated with Wilmington Police Department, Emergency Response Units, and Motor Assistance Patrol to patrol the alternate and nearby routes to respond to accidents and/or emergency situations.
- System redundancy – The availability of I-95 in Wilmington and I-295 in New Jersey as parallel routes lessened the impact of the bridge closure. This underscored the importance of redundancy.

In the case of the I-495 bridge closure, DelDOT was able to control traffic via effective planning by implementing lane closures and changes in lane configurations along both I-495 and nearby roadways as well was implementing ramp closure points. DelDOT was also able to utilize temporary traffic signals to control the flow of traffic at intersections that needed additional control. Not only did this mitigate the traffic impacts of the closure, but it also safely funneled traffic onto the primary alternate route, I-95. DelDOT and its team of engineers also created Maintenance of Traffic (MOT), Alternate Route, and Portable Changeable Message Signs (PCMS) plans to guide road users away from and off I-495. These lessons learned also helped to expedite the construction duration and get the bridge reopened in a matter of three months.

Traffic Monitoring

Traffic monitoring refers to DelDOT's ability to monitor how Delaware's transportation system operates and is impacted by the closure of Bridge 1-813. The lessons learned regarding traffic monitoring are the value of leveraged real-time traffic data and the importance of a centralized signal system:

- Leveraged real-time traffic data – The use of real-time traffic data via traffic monitoring devices was a key aspect of DelDOT's Transportation Management Center's goal to control and monitor Delaware's transportation system and inform road users. Traffic sensor cameras were DelDOT's 'eyes on the site' and allowed engineers to determine where congestion, delay, and accidents were occurring. Bluetooth detection devices were used to gather travel times, distance traveled, and speed to communicate travel delay to road users and system detection devices were used to collect volumes along the roadway.
- Centralized signal system – During the closure, DelDOT did not have access to remotely control the signals within the City of Wilmington which created a bit of a setback. Instead of having all Delaware signals on a centralized system to control in the office, DelDOT engineers had to travel in the congested traffic to manually retime signals. Not only did this take time itself to complete, but it was also very inconvenient. The I-495 closure emphasized the importance of having all signals on a centralized system and DelDOT has since updated their system. Today, for the current I-95 Wilmington Viaduct project, all signals within the area are on a centralized system and DelDOT can remotely control all signals across the state. In addition to updating the signal system, DelDOT also updated their system of reporting. As soon as an incident report comes in, DelDOT sends engineers directly into the field to inspect the issue at hand.

In the case of the I-495 bridge closure, DelDOT monitored traffic via the use of traffic monitoring devices such as traffic sensor cameras, Bluetooth detection devices, and system detection devices. Using this real-time traffic data in conjunction with having a centralized signal system, DelDOT was able to remotely monitor traffic and determine traffic impacts caused by the closure. Not only was this data used for research purposes, but it was also used to inform road users of delays and expected travel times.

Informing Road Users and Others

DelDOT's ability to inform road users was also a major key in mitigating congestion during the bridge closure. The lessons learned regarding informing road users is the importance of effective communication and functional teamwork:

- Effective communication – DelDOT not only had to communicate within the transportation department but also with the geotechnical, structural, maintenance, operations, and management specialists. DelDOT also oversaw all operations of its contractor and subconsultants to ensure the full scope of the project was in place and accounted for. Recognizing that DelDOT sourced materials and machines from across the United States to expedite the project, accommodate the height restrictions and address the contamination issues. In addition, DelDOT directly communicated with the media and with the public via DelDOT's radio station, website, and app. Utilizing existing plans (specifically, Maintenance of Traffic, Alternate Route, and Portable Changeable Message Sign plans), DelDOT was able to directly communicate the closure and suggested routes to road users.
- Functional teamwork – DelDOT's leadership rapidly assembled a multi-disciplinary team of experts to develop a solution to the initial problem. This team was required to work collaboratively and cooperatively. To facilitate the reopening of the bridge, DelDOT coordinated with Governor Mario M. Cuomo Bridge engineers to bring in pre-made reinforced steel cages and steel casings from Oklahoma and Washington. DelDOT worked with DART, SEPTA, neighboring states, agencies, engineers, politicians, the police department, and the City of Wilmington community to provide updates and information on travel impacts to enhance coordination and decision-making.

In the case of the I-495 emergency bridge closure, DelDOT informed road users by placing signage along the impacted routes and directly communicated with road users via the DelDOT website, app, and radio station. DelDOT also communicated with nearby states whose road users were also impacted by the closure such as Maryland, New Jersey, and Pennsylvania. By utilizing and communicating with patrol vehicles and the police department, DelDOT was able to quickly respond to any emergencies on site to get the issue resolved and continue the flow of traffic.

CONCLUSION

In the case of the I-495 emergency bridge closure over the Christina River in Wilmington, DE, a plethora of travel impacts arose because of four out of 37 piers being compromised and deeming the structure unsafe. Due to a 50,000-ton dirt stockpile placed near piers 11, 12, 13, and 14, the substructure of the bridge failed, which resulted in nearly a three-month closure. The 40-year-old, 39-span bridge serviced 90,000 vehicles per day to and from Delaware, Maryland, New Jersey, and Pennsylvania. The repair project was complex as the closure impacted thousands of users and non-users, involved many different engineering disciplines, firms and organizations, and required coordination among local, state, and federal government agencies. In addition to project coordination, the project was also complex in the terms of timing phase one, temporary repairs, and phase two, repairs, while minimizing the length of the closure.

The bridge closed on June 2, 2014 and the southbound direction reopened to traffic on July 31, 2014 while the northbound direction reopened to traffic on August 23, 2014. DelDOT, its contractor, and consultants worked around the clock to get the bridge reopened. Phase one of the project consisted of temporary repairs to reopen the bridge to traffic ($40 million), while phase two consisted of permanent repairs to replace the temporary repairs ($15 million). DelDOT worked to route traffic away and off Bridge 1-813 and onto nearby roadways while also developing an expedited plan to close the bridge without creating chaotic and unsafe traffic conditions.

This case showcases the multi-modal, multi-attribute, multi-objective, and multi-assets tradeoffs involved in transportation repair and rehabilitation projects which ultimately impacts the many stakeholders engaged in complex projects. In this thesis tradeoffs are described as user shifts; agency plans; and innovative construction methods. Examples of these tradeoffs include:

- User shifts - Thousands of road users were forced to shift their time-of-day travel, mode of travel, and/or route.
- Agency plans – DelDOT, as the owner of the bridged, faced many tradeoff decisions. The initial decision to close the bridge balanced safety and disruption. Charting a course of action involved tradeoffs between costs and time. Developing a traffic mitigation plan-imposed delays on users of other routes. Ultimately DelDOT’s plans lead to the success of the project from a traffic mitigation, management, and maintenance standpoint.
- Innovative construction methods – From innovative sourcing of materials to coordinated scheduling to stage the repair and prioritize opening the direction of travel that experienced the greatest traffic impact (in this case, this was the southbound direction), a variety of construction methods accounted for tradeoffs among time and costs, different groups of users, and short-term and long-term disruptions.

Table 3-3 summarizes the connection between the strategies: user shifts, agency plans, and innovative construction and the objectives: minimizing impacts of the immediate closure, minimizing impacts during the repair, and maximizing long-term serviceability.

The analysis of traffic impacts due to road planned and unplanned is a rich area for further research. Additional analysis is reported in Withers (2021) and Lin (2016). This work could then build on the type of analysis reported in Zhu and Levinson (2012) and connect to more recent work on resilience (McNeil et al., 2019).

In closure, the I-495 emergency bridge closure serves as a guide for future transportation repair and rehabilitation projects, both with immediate bridge/road closures (unplanned construction projects) and scheduled bridge/road closures (planned construction projects). This case of Bridge 1-813 has created a learning environment for engineers across the county, allowing firms and agencies to enhance their organization structure. During the I-495 bridge closure, DelDOT continuously monitored traffic and established multiple efforts to relieve congestion. DelDOT provided detour routes for motorists and trucks, adjusted the signal timing of nearby intersections, installed temporary signals, worked with Delaware police departments to guide traffic, and prevent confusion, restriped I-95 creating three travel lanes, and suspended construction projections on the outlined detour routes. In less than a week, DelDOT successfully planned an ‘unplanned’ project and had both directions of I-495 reopened in a matter of three months. The overall project highlights a strong team of knowledgeable engineers, contractors, and planners who repaired and rebuild a structurally deficient and unsafe bridge in less than three months. Hats off to DelDOT!

Table 3-3 Summarized Strategies and Objectives

Strategies		Objectives		
		Minimize Impacts of Immediate Closure	Minimize Impacts During Repair	Maximize Long-Term Serviceability
User Shifts		Alternate routes	Alternate routes, time shifts, alternate modes	-
Agency Plans	Control	Emergency response		
		Emergency contracting		
		System redundancy		
	Monitor	Real time traffic data		
		Centralized signal control		
	Inform	Users, public, contractors, partners		Leadership, partners, contractors
Innovative Construction Methods		-	Sourcing of materials and coordination	Minimal disruption, maximize structural health

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CHAPTER 4

Maintaining Shared Auto, Bike and Pedestrian Facilities: A Multi-objective Approach

INTRODUCTION

The importance of providing an efficient multi-modal transportation system for travelers has long been recognized. Such systems contribute to quality of life, community livability, and healthy living. They further offer sustainable transportation solutions. Programs and initiatives, such as Smart Growth, Complete Streets, Context Sensitive Design, Safe Routes to School, Recreational Trails Program, Transportation Enhancements and Active Living. These programs have contributed to growing awareness of the value of access to non-motorized modes of transportation and transit, and the different connections between different modes. Many such programs are intended to encourage transit usage, and non-motorized modes of travel while also accommodating auto travel. Legislation, including The Americans with Disabilities Act (ADA), The Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU), The Safe and Complete Streets Act, and the Safe Routes to School Act, The Active Communities Transportation (ACT) Act, and The Livable Communities Act, have also emphasized these modes (de Zeeuw & Flusche, 2011).

Professional organizations such as the Transportation Research Board (TRB) and American Society of Civil Engineers (ASCE) have also focused resources on improving non-motorized and active transportation (Transportation Research Board, 2022). The COVID-19 Pandemic saw unprecedented levels of bicycle and pedestrian activity in dense urban areas, such as New York City, which led to the addition of new supporting facilities (Buehler and Pucher, 2021a).

Common to all these program and initiatives is that different modes share the right of way, and, in some cases, specific facilities, such as dedicated bike and pedestrian paths or urban bike lanes (e.g., complete streets). While guidelines are readily available for the design of such facilities (see, for example, (Steiner, et al., 2012; WSP | Parsons Brinckerhoff, 2017; American Association of State Highway and Transportation Officials (AASHTO), 2012), little attention has been paid to supporting multi-modal travel during maintenance and reconstruction. Although the Manual of Uniform Traffic Control Devices (MUTCD) and the AASHTO design guide indicate that motorists, pedestrians (including persons with disabilities) and bicyclists must be accommodated through a temporary traffic control zone (Huber, et al., 2013), experience suggests otherwise. Projects, such as roadway repaving and reconstruction, generally pay little attention to disruptions to pedestrians and bicyclists beyond putting up a sign indicating the pedestrian or bicycle route is closed. Furthermore, maintenance of pedestrian and bicycle facilities appears to be haphazard and unplanned, and are rarely coordinated with maintenance actions taken on roadways.

Given the different maintenance needs for different types of facilities this research explores the issues involved in accounting for disruption to all modes and the strategies for maintenance decision-making and scheduling that recognize all users. The objective is to develop strategies for selecting maintenance actions for bike, pedestrian, and auto facilities that share the right of way accounting for disruptions to all modes. The proposed strategies build on principles of asset management and work with the construct of the transportation system as a sociotechnical system. Given that these decisions are commonly the responsibility of municipal governments with few resources, ultimately, guidelines are needed to support municipal governments and reduce the need for onerous data collection and modeling efforts.

Consistent with current practices in asset management and performance-based planning, maintenance and rehabilitation decisions rely on performance measures for target setting, prioritization, and optimization of project choices. The objectives of the work completed and described in this chapter were to: (1) explore potential performance measures related to relevant objectives in the context of the shared-use facility considering the perspectives of users from different modes and of different capabilities; (2) develop a framework and specific methodological steps for quantifying the effects of a maintenance or rehabilitation project plan in terms of the developed performance metrics on each user group; and demonstrate the importance of coordination in maintenance and rehabilitation planning to support sustainable, livably and healthy urban environments for all users.

The chapter is organized into six additional sections. The following section reviews what we know from the literature. This is followed by a section on performance measures and then general concepts used in the formulation of the problem. A discussion of the data required and a realistic network to explore options is presented. Finally, the anticipated challenges and expected results are presented.

WHAT DO WE KNOW FROM THE LITERATURE

This work builds on the literature from eight different areas: socio-technical systems, current practices for facility design of multimodal facilities, asset management, condition assessment of bicycle and pedestrian facilities, walkability and bikeability scores, levels of service, potential maintenance actions and costs, and multi-criteria analysis for bicycle and pedestrian facilities. The section concludes with a summary of the gaps in the literature.

Sociotechnical Systems

Infrastructure systems in general and transportation systems are characterized as socio-technical systems (Little, 2004; Ottens, et al., 2006). A socio-technical system is conceptualized as a system in which end users play an active role in determining how well technical components are able to serve them (Vodopivec & Miller-Hooks, 2019). While much of the relevant literature on socio-technical infrastructure systems focuses on resilience, infrastructure interdependencies, and new technology, the construct applies to systems, such as the roadway, bicycle, and pedestrian systems that we are concerned with in this chapter, because technical decisions should reflect user experiences, perceptions and behaviors. For example, level of service (LOS) for bicyclist and pedestrians vary by population groups, such as commuters versus recreational users, or visually or mobility impaired pedestrians. Using the characterization presented by Ottens et al. (Ottens, et al., 2006), Table 4-1 shows some of the relationships between actors (users, owners, operators), and technical elements (vehicles, infrastructure, communication, management systems) and social elements (institutions, constraints and regulations, demographics). Relationships are characterized as physical (direct connection), functional (fulfils a function within or for another element), intentional (actor determines an intentional state), or normative (rules connect elements). By explicitly identifying these relationships, we are able to understand the objectives and constraints of the different actors and the relationships among the actors.

Table 4-1 Examples of Relationships in socio-technical systems

Relationship	Example	Physical	Functional	Intentional	Normative
Technical-Technical	Vehicles and the infrastructure	x	x		
Technical-Actor	Rider on bicycle; pedestrian using a sidewalk	x	x	x	

Actor-Actor	Pedestrian reporting a malfunctioning light to a municipality	x	x	x	
Actor-Social	Obeying signals; not parking on the sidewalk		x	x	x
Social-Social	ADA and local ordinances requiring sidewalks to be clear of snow and ice		x		x
Social-Technical	Speed limits; accessibility		x		x

Current Practices for Facility Planning and Design

The design of multi-modal facilities in the shared right-of-way requires consideration of efficiency, safety, accessibility, mobility and sustainability. There is a growing body of literature on complete streets and active transportation design and implementation. Basic parameters are laid out in design manuals (Steiner, et al., 2012).

More recent projects develop guidance documents for identifying and selecting projects. For example, Goodman et al. (Goodman, et al., 2016) provide guidance for integrating an on-road bicycle network into resurfacing project. In another example, the ActiveTrans Priority Tool (Langerwey, et al., 2015) was developed as part of NCHRP 803: Pedestrian and Bicycle Transportation Along Existing Roads. The project provides guidance to prioritize improvements to pedestrian and bike facilities. Nine common factors are considered in the prioritization process:

- Stakeholder input
- Constraints
- Opportunities
- Safety
- Existing conditions
- Demand
- Connectivity
- Equity
- Compliance

A large body of literature has also emerged on Complete Streets. Several states have developed guidelines, for example, New Jersey (WSP | Parsons Brinkerhoff, 2017) and Delaware (Scott et al., 2012). Still other publications look to linking these modes and strategies to sustainability (Buehler and Pucher, 2021b; Patterson, 2013; Oswald Beiler and Waksmunski, 2015). Pais et al. (2022) serves as another more recent example.

Asset Management

Similarly, the maintenance of roadways has received considerable attention over the last four decades, building on work on pavement management and evolving into the more general work on asset management that recognizes the value of a data driven decision process that includes both goals and resource constraints. Literature on roadway paving, road reconstruction, and asset management includes what decisions to make and when, life cycle cost analysis, deterioration models, strategies for making optimal decisions, and scheduling. A review of this literature is beyond the scope of this report.

Condition Assessment of Sidewalks and Bicycle Facilities

Condition data is required to determine maintenance decisions. Most of the literature on sidewalk/footpath condition is associated with strategies and guides for selecting actions. In this section, the focus is on the condition; actions, and strategy selection are presented in Chapters 6, 7 and 8. For example, Huber et al. (Huber, et al., 2013) identify common problems influencing safety and requiring maintenance. These include:

- Infrastructure, including structural problems resulting in surface defects (uplift or settlement, shrinkage, raised or heaved, and sagging), curb ramps, crosswalk markings, signals, and signage, and
- Seasonal maintenance, including snow and ice removal, deformation due to extreme heat, and vegetation overgrowth and debris accumulation.

However, quantifying condition requires clear descriptions of either the problem or the current status. For sidewalks, the ADA guidelines (Huber, et al., 2013) require accessible routes to have stable, firm and slip-resistant surfaces, surface discontinuities that do not exceed half an inch (13 mm), maximum running grade of 5%, maximum cross grade of 2%, minimum clear width of 4 feet (1.2 m), and limits on protruding objects. A sidewalk condition index (SCI), modeled on the pavement condition index using a weighted average of the severity and density of measured distresses, captures degradation (Corazza et al., 2016). A correction is applied to ensure that the SCI is between 0 and 100.

Strategies for getting information/inspection (modified from (Huber, et al., 2013)) include:

- Community-wide inspection
- Zone inspections
- Spot inspections
- Actions following a complaint or injury
- Participatory planning/ Citizen science/ Community volunteers/ Crowdsourcing (Qin, et al., 2018)

A critical element is the documentation of the inspection (the asset register in asset management terminology). These inspections can also be supported by tools, such as GPS/GIS and devices, such as inclinometers and video-based inspection (for example, sensors mounted on a Segway).

In another example, Frackleton (2013) collected pedestrian facility data in the field using a mobile Android application. A cell phone with the app installed should be attached to a basic manual wheelchair. A tablet collects data that is used to evaluate where sidewalks may be in need of repair or reconstruction based on ADA accessibility guidelines.

Similar approaches are used to represent bicycle facility condition. Elsaid et al. (2020) use traditional pavement performance indicators, including the International Roughness Index (IRI), structural strength index, and pavement condition index (PCI). Vavrova and Chang (2019) use a bikeway pavement condition index (BPCI) based on a score of 0 to 100, where below 65 is considered poor condition, 84 to 65 fair condition and above 84 is good condition. The BPCI is based on a visual assessment of potholes, cracking, debris, gravel and draining grates. Vavrova and Chang also use the remaining life of pavement marking as a condition measure, where brand new markings have a remaining life of four years and markings needing maintenance have no remaining life. The Highway Capacity Manual (Transportation Research Board, 2016) provides a qualitative description of pavement condition ratings for bicycles as part of the LOS calculation. The condition ratings on a scale of 0 to 5 are shown in Table 4-2.

Table 4-2. Pavement Condition for Bicycle Level of Service (Transportation Research Board, 2016)

Pavement Condition Rating	Pavement Description	Motorized Vehicle Ride Quality and Traffic Speed
4.0 to 5.0	New or nearly new superior pavement. Free of cracks and patches.	Good ride
3.0 to 4.0	Flexible pavements may begin to show evidence of rutting and fine cracks. Rigid pavements may begin to show evidence of minor cracking.	Good ride
2.0 to 3.0	Flexible pavements may show rutting and extensive patching. Rigid pavement distress may have a few joint fractures, faulting, or cracking.	Acceptable ride for low speed traffic but barely tolerable for high speed traffic

1.0 to 2.0	Distress occurs over 50% or more of the surface. Flexible pavement may have large potholes and deep cracks. Rigid pavement distress includes joint spalling, patching, and cracking.	Pavement deterioration affects the speed of free-flow traffic; ride qualitynot acceptable
0.0 to 1.0	Distress occurs over 75% or more of the surface. Large potholes and deep cracks exist.	Passable only at reduced speed and considerable rider discomfort

Complexities to consider include:

- Different owners (in the US, generally property owners are responsible for sidewalks);
- Resource constraints particular to non-motorized transportation; and
- ADA compliance.

Walkability and Bikeability

The concepts of walkability and bikeability are useful. Walkability indices indicate the opportunities for pedestrian-oriented activity in an area. They are composite measures that vary in scale and method, but all attempt to capture characteristics of the environment. Ideally, these include physical conditions, capacity and desirability.

Agampatian (2014) provides a summary of walkability measures that are largely aimed at encouraging walking as part of healthy living. An enhanced summary is included in Table 4-3. Research in this area is strongly influenced by funding from a Robert Wood Johnson Foundation “Active Living” initiative. Other studies of bikeability include Reggiani et al. (2021), Karolemeas et al. (2022), and Hartano (2017). Most studies focus on investments to improve access. However, Epperson (1994) recognizes the role of condition in bikeability.

Another approach to walkability has been fueled by the private sector supporting the real estate industry. The Walk Score was first published in 2007 (https://www.walkscore.com/) and reflects the proximity and density of walkable destinations rather than physical conditions, such as the presence and condition of sidewalks and ramps, and grades (Li, et al., 2018). The site also includes a Transit Score and a Bike Score. The definitions for these scores are as follows (https://www.walkscore.com/):

- Walk Score: measures the walkability of any address based on the distance to nearby places and pedestrian friendliness.
    - Walker’s Paradise (90-100): Daily errands do not require a car
    - Very Walkable (70-89): Most errands can be accomplished on foot
    - Somewhat Walkable (50-69): Some errands can be accomplished on foot
    - Car Dependent (25-49): Most errands require a car
    - Car Dependent (0-24): Almost all errands require a car
- Transit Score: measures how well a location is served by public transit based on the distance and type of nearby transit lines.
    - Rider’s Paradise (90-100): World-class public transportation
    - Excellent Transit (70-89): Transit is convenient for most trips
    - Good Transit (50-69): Many nearby public transportation options
    - Some Transit (25-49): A few nearby public transportation options
    - Minimal Transit (0-24): It is possible to get on a bus
- Bike Score: measures whether an area is good for biking based on bike lanes and trails, hills, road connectivity, and destinations.
    - Biker’s Paradise (90-100): Daily errands can be accomplished on a bike
    - Very Bikeable (70-89): Biking is convenient for most trips
    - Bikeable (50-69): Some bike infrastructure
    - Somewhat Bikeable (0-49): Minimal bike infrastructure

In the context of smart growth, the US Environmental Protection Agency has developed the National Walkability Index (https://www.epa.gov/smartgrowth/smart-location-mapping#walkability). The index is based on a block group and EPA also provides data for major metropolitan areas through the Smart Location Databased (SLD) (U.S. Environmental Protection Agency, 2021). The index uses four measures (intersection density, transit proximity, employment mix, and employment/ household mix) for each block group. Each measure is placed in one of 20 quartiles and then weighted according to the ratio 1/3: 1/3:1/6:1/6. The index is a score of 1 to 20 with 1 being the least walkable block groups.

Table 4-3 Walkability Indices Reflecting Desirability (Modified from (Agampatian, 2014))

Weights	Variables	Unit of Analysis	Score	Source
Based on prior evidence (for example, street connectivity)	Net residential density Retail floor area ratio Land use mix (consider 5 land use types: residential, retail, entertainment, office, and institutional) Intersection density	Predefined spatial unit	z-score	(Frank, et al., 2009)
Equal	Net residential density Retail floor area ratio Entropy based measure of land use mix Intersection density	Block group	z-score	(Lachapelle, et al., 2009)
Based on prior evidence	Net residential density Commercial density Land use mix Street connectivity	Block group with a 1-km buffer	z-score	(Frank, et al., 2010)
Not applicable	Negative of average block size % of all blocks with areas < 0.01 square miles The number of 3-, 4-, and 5-way intersections divided by the total number of road miles	Block group	z-score	(Doyle, et al., 2006)
Equal	Car ownership per household Population density per km^2 of residential area Density of all retail service per 10 thousand ppl Average distance from residential point to the nearest five retail locations Rates of drug-related and violent crime rate		Activity Friendly Index (AFI) =average of scores 0-10 for each variable	(Glazier & Booth, 2007)

Levels of Service

The concept of LOS is widely used to evaluate the performance of motorized modes of transportation, particularly passenger automobiles and trucks. Over the last three decade these concepts have been extended to multimodal transportation, including bicycles and pedestrian. While the concepts build on those used for automobiles, the concepts and processes have evolved from the early work on bicycles (Landis, et al., 1997) and pedestrians (Landis, et al., 2001) to being represented in several chapters of the current Highway Capacity Manual (Transportation Research Board, 2016). LOS captures the relationships between the amount and nature of demand, and the physical facility.

In the case of bicycles, the LOS is evaluated for a segment (where a segment includes the intersections) or link that is either a lane shared with motorized vehicles or an exclusive bike lane. The LOS is evaluated separately for travel in different directions. The performance measures are bicycle travel speed and bicycle LOS score, where the score is an indication of the perceived bicycle experience (Transportation Research Board, 2016). The bicycle LOS score includes an adjustment F_p based on pavement condition, $P_{c,}$ as shown in Table 4-2, where (Transportation Research Board, 2016):

$$F_p = \frac{7.066}{P_C^2}. \tag{4.1}$$

In the case of pedestrians, LOSis evaluated for a segment or link, for each side of the street. Performance measures include: pedestrian travel speed, pedestrian space and pedestrian LOS score, where the score is an indication of the perceived pedestrian experience (Transportation Research Board, 2016).

In addition, Chapter 24 of the Highway Capacity Manual considers off-street pedestrian and bicycle facilities, and Chapter 35 addresses the special case of shared use paths.

Maintenance Costs and Actions

Pavements

The cost of different maintenance actions is developed from (VDOT, 2016; PennDOT, 2017; FDOT, 2020; ARTBA, 2020) and provided for primary and secondary roads in Table 4-4. Costs are reported in USD/m^2 and the total cost can be calculated using the components' length and width (~3.7 m (12 feet) per lane).

The duration of different maintenance actions is inferred from (ADOT, 2018; PennDOT, 2019). It is further assumed that no action takes more than 2 years and no Major action takes more than a year to complete for a component. This can be justified by assuming multiple maintenance activities at a time for longer and multi-lane components. These durations are provided in Table 4-5.

Table 4-4 Maintenance Action Costs for Asphalt Pavements, Reported in USD/m^2.

Actions	Description	Cost (USD/m2) Primary	Cost (USD/m2) Secondary
Do Nothing	NA	0.00	0.00
Minor Repair	Moderate patching (<10%), surface treatment, partial depth patching, thin overlay	16	10
Major Repair	Heavy patching (<20% of the pavement area), full depth patching, structural overlay	68	52

Reconstruction	Replacing the entire pavement section	330	250

Table 4-5 Maintenance Actions Duration in Days per Lane-mile.

Actions	Days per lane-mile	Additional days per mile for shoulder, etc.
Do Nothing	0	0
Minor Repair	3.5	1
Major Repair	6.5	2
Reconstruction	32	10

Sidewalks and Bicycle Facilities

Obtaining data related to the nature, costs, needed materials, durations and constraints associated with maintenance actions for sidewalks and bicycle facilities is essential for decision making. Websites for a variety of jurisdictions provide data, but with inconsistent terminology and units of analysis. This data is synthesized and summarized in Table 4-6.

Table 4-6. Maintenance Costs for Bicycle and Sidewalk facilities

Facility Type	Action	Cost ($/mile/year)	Source
Bike lanes	Maintain/repair pavement and landscaping	$1,300	(Bethlehem, New York, n.d.)
Bike routes	Maintain/repair pavement and landscaping	$635	
Paths	Maintain/repair pavement and landscaping	$1,600	
Sidewalk	Replacement	$528,000	
Bike lanes	Thermoplastic markings	$51,000	(Vavrova & Chang, 2019)

Decision-making Strategies for Bicycle and Pedestrian Facilities

A literature review focusing on the maintenance of bicycle and pedestrian facilities provides an overview of the current state of the art. Some studies focus on one specific measure of performance, for example, condition, safety or risk. Corazza et al. (2016) used the SCI to optimize maintenance decisions. Qin et al. (2018) use prioritization information and usage frequency to determine the benefit associated with the repair of a specific pedestrian network segment. The segments that have high intrinsic value due to priority and/or usage generate higher benefit if repaired. Sirota (Sirota, 2008) prioritizes a given list of existing unsafe sidewalk locations needing maintenance or rehabilitation using a direct measure of pedestrian safety, namely, quality-adjusted life years lost per year.

Frackleton (2013), Sousa et al. (2017), Elsaid et al. (2020), Vavrova and Chang (2019), Zhu and Zhu (2020), and Pais et al. (2022) all develop models aimed at decision making using multi-criteria optimization. Frackleton et al. used a weighted ranking system to prioritize pedestrian projects based on condition data, safety indicators, pedestrian activity and demographic data. Sousa et al. use multicriteria classifying methods (4 classes by a performance matrix) to assess sidewalk performance (23 sidewalks in the city of Coimbra, Portugal). Elsaid et al. use bike demand (by GPS) and pavement deterioration prediction to produce optimal strategies of reconstruction and preventive maintenance for roads and on-street bikeways. Integer Linear Programming (ILP) is used to maximize pavement condition & minimum required budget (2 scenarios in Montreal). Vavrova and Chang incorporate bikeway maintenance and new build plans into TAM practices through assessment, prioritization, scenarios, and reporting using a budget scenario analysis for 70 block-long sections in San Francisco, CA. Zhu and Zhu propose a multi-objective integer linear programming model that is formulated to determine the spatial layout of bike-way networks and types of bike-way links for retrofitting existing cycling infrastructure for commuter cyclists. The objective maximizes accessibility, minimizes the number of intersection, maximizes bicycle LOS and minimizes total construction cost. Pais et al. (2022) consider cyclists' comfort, safety, conflicts, width, intersections and lighting to determine maintenance actions for a cycle network in Portugal. They found that safety and intersections were the most important criteria.

Chang et al. (2022) looked at integrating on-street bikeway maintenance activities with pavement management. Using decision trees based on the type of bikeway and the PCI, treatments are identified. Their decision trees assume that shared lanes use the same treatments as roadway sections. This assumption is used in this analysis.

Gaps in the Literature

There are significant gaps in the literature. Specifically:

- condition assessment processes for bike and pedestrian facilities are not rigorous and there are few deterioration models;
- the relationship between the demand for non-motorized transportation and the condition of facilities is poorly understood;
- disruptions to non-motorized transportation facilities due to roadway repair, repaving and resurfacing are ignored; and
- the response of non-motorized transportation users to disruptions is not understood or modeled despite the potential for creating equity issues, e.g., mobility impaired users will experience disproportionately longer, and often less safe, trips when access to curb cuts or paved sidewalks is disrupted.
- This effort sought to fills these gaps as described in this and other chapters.

POTENTIAL PERFORMANCE MEASURES

The literature and examples of transportation performance measures emphasize the importance of connecting the measures to the goals and objectives of the analysis. The acronym SMART – specific, measurable, achievable, relevant and timebound – captures the desirable attributes of performance measures, which in this context, are outcome based (Zietsman, Ramani, Potter, Reeder, & DeFlorio, 2011). As such, they need to be comprehensive, consistent, measurable, context specific, and informed by value, influence, and purpose (Chinwe Achebe, 2021). These attributes of performance measures also reflect the relationships between the elements of the socio-technical system and the different types of relationships (physical, functional, intentional, and normative).

Recognizing that transportation infrastructure is a complex sociotechnical system means that the performance measures must capture both the technical and social aspects of the system. Performance measures are key to being able to make decisions that reflect the needs of individuals, connect to community, regional or state-wide goals, and capture the technical attributes of the systems. While performance measures can be inferred from much of the literature cited in the previous section, these measures are not developed systematically or connected to overall goals. FHWA's Guidebook for developing pedestrian and bicycle performance measures elaborates on potential performance measures, as well as connecting such measures to community goals (Semler, et al., 2016). The community goals are connectivity, economy, equity, health, livability, and safety. The transportation measures are grouped to represent accessibility, compliance, demand, infrastructure attributes, mobility, and reliability, which in turn connect to specific measures as shown in Table 4-7.

Table 4-7 Goals Applicable to Performance Measures (Semler, et al., 2016)

Transportation Measure	Performance Measure	Connectivity	Economic	Environment	Equity	Health	Livability	Safety
Accessibility	Access to community destinations	X	X	X	X	X	X	X
Accessibility	Access to jobs	X	X		X			
Compliance	Adherence to accessibility laws	X	X		X	X	X	X
Compliance	Adherence to traffic laws					X		X
Mobility	Average travel time	X	X		X		X	X
Mobility	Average trip length	X	X		X		X	X
Infrastructure	Connectivity index	X	X		X		X	X
Reliability	Crashes				X	X	X	X
Infrastructure	Crossing opportunities	X			X	X	X	X
Mobility	Delay				X		X	X
Accessibility	Density of destinations	X	X		X	X	X	X
Infrastructure	Facility maintenance	X			X		X	X
Accessibility	Job creation		X	X				
Infrastructure	Land consumption		X				X	
Accessibility	Land value		X					
Mobility	Level of service				X		X	X
Infrastructure	Miles of pedestrian/bicycle facilities	X			X	X	X	X
Mobility	Mode split			X	X	X	X	
Infrastructure	Network completeness	X	X	X	X	X	X	X
Mobility	Pedestrian space		X		X		X	X
Demand	Person throughput		X		X			
Mobility	Physical activity and health				X	X	X	
Accessibility	Population served by walk/bike/transit	X			X	X	X	X
Accessibility	Retail impacts		X					
	Route directness	X	X	X	X		X	X
Infrastructure	Street trees			X		X	X	X
Demand	Transportation disadvantaged population served	X			X			
Reliabilty	User perceptions					X	X	X
Mobility	Vehicle miles traveled (VMT) impacts			X		X	X	X
Demand	Volume			X		X		X

Of the seventy-one performance measures identified in the literature, those most relevant to maintenance decisions are shown in Table 4-8. Missing are sustainability measures. Of the measures in the table, several are determined by other measures. For example, delay is determined by volume and travel speed, which in turn is influenced by performance measures, such as network attributes, that do not change with maintenance. Schonfeld et al. (2016) found that maintenance directly impacts safety. Others, such as equity, are captured by looking at specific groups of users. Most importantly, the measures selected meet the desired attributes for performance measures in terms of being comprehensive, consistent, measurable, context specific, and informed by value, influence, and purpose. As the focus herein is on maintenance decisions rather than network design or improvement, how these performance measures change either during or after maintenance is of great interest. Ultimately, whether degradation of a performance measure, such as person throughput or travel time, during maintenance warrants gains in condition or travel time after maintenance is completed needs consideration. This analysis accounts for the costs of maintenance, user costs and ideally social costs over the life cycle. Such tradeoffs are critical to decision making. Furthermore, drawing on the work of Chinwe Achebe (2021), these measures are informed by the value of the assets to users, the influence of maintenance decisions, and the purpose of delivering a service over the lifecycle.

Table 4-8 Performance Measures Relevant to Maintenance of Bicycle and Pedestrian Facilities

Type	Description	Scale	Source
Accessibility	Population served by walk/bike/transit	Community	Semler 2016
Condition	Crosswalk markings, Curb ramps, Signage, Signals	Location	Huber 2013
	Extreme heat, Snow and ice, Structural problems, Surface discontinuities, Vegetation growth & debris accumulation	Link	
	Facility maintenance	Community	Semler 2016
Demand	Person throughput, Disadvantaged population served, Volume	Community	Semler 2016
Mobility	Average travel time, Average trip length, Delay, LOS, Vehicle miles traveled (VMT) impacts	Community	Semler 2016
	Bicycle LOS score, Bicycle travel speed, Pedestrian LOS score, Pedestrian space, Pedestrian travel speed	Segment or Link	HCM 2016
Safety	Crashes	Community	Semler 2016

FORMULATION OF THE PROBLEM

Our objective is to identify and schedule maintenance decisions for roadway, bicycle and pedestrian facilities that recognize the physical interdependencies that occur due to shared right-of-way and the related disruptions that non-motorized users experience. At the same time, there are limited resources for maintenance projects. Maintaining performance while minimizing costs is critical. Projects can be accelerated, bundled, decoupled, or coordinated to address user impacts while also addressing the larger goals of accessibility, condition, demand, mobility, safety and sustainability.

Given that the budget for bicycle and pedestrian maintenance is very small compared with that for roadway pavements, for a planned set of pavement-related projects, the objective is to determine the relevant sidewalk and bicycle facility maintenance activities and project timings that optimize the performance measures across a community. The focus is on selecting sidewalk and bicycle facility mainteancne acitivities and then schedule the activities for all modes to meet specific objectives.

To this end, a multi-objective and multi-modal approach is taken in which modal network representations are connected at intermodal connections, here at crosswalks and entry points to separate facilities, such as bikeways. A mathematical formulation is developed on this representation. Solution of the formulation provides a schedule of improvement actions across modes that maintains minimum serviceability levels on all modes for all user classes and optimally applies any additional resources to balance elective improvements over the various modal users. Improvements can also increase capacity or accessibility for some or all users on one or more modes. The objective balances these improvements against the negative impact of their execution on users. These impacts are both direct and indirect, the latter arising as improvement activities on one mode impact users or subgroups of users of the other modes. The model incorporates user travel decisions under routine and disrupted transportation environments. Solution provides the set of Pareto optimal schedules. A best compromise solution will be identified through an analysis of tradeoffs and consideration of both operator and user perspectives. Quicker, reduced, weighted objective functions will be considered.

DATA REQUIRED AND EXAMPLE NETWORK

To explore alternative formulations and solutions, data for a modest, realistic example network were assembled. The network is based on actual facilities in the business district of Newark, Delaware, as shown in Figure 4-1. The network and data are realistic rather than real as some assumptions had to be made. The assets are selected roads, sidewalks, bicycle lanes and bicycle paths. The network is modeled by 17 nodes and 50 links. Link attributes include the number of travel lanes and width, pavement condition, bike facilities, sidewalk width, walkability and bikeability score. Origin-destination flows for each node pair during the morning peak are estimated for each mode totaling 15,500 automobile, 380 bicycle and 360 pedestrian trips per hour. The facilities are assumed to be in good physical condition and are not congested. The majority of the network is wheelchair accessible. Some links are perceived as dangerous on a bicycle, trashcans and debris often impede pedestrians on the sidewalk, and recent reconstruction projects disrupted travel for several months. Additional scenarios associated with events drawing more bicyclists and pedestrians are also studied.

Newark is home to the University of Delaware and located just off I-95 between New York city and Washington, D.C. The assets are select roads, sidewalks and bicycle paths bounded by Cleveland Ave. in the north, Delaware Ave. in the south, Library Ave. in the east and College Ave. in the west as shown in Figure 4-2. Main Street is the main east-west road and the commercial center of town. Main Street is one-way west bound and Delaware Ave. to the south is one-way east bound. The network representation of the assets of interest is shown in Figure 4-3, and the labeled network is shown in Figure 4-4.

For each link, the attributes are shown in Table 4-9. On Main Street and Delaware Ave., the configuration for each link is the same and the links are grouped together. In all cases, each lane is assumed to be 12 feet wide. In addition, a walkability and bikeability score (from http://walkscore.com) is provided for each link (Table 4-10).

Link usages by various hours of the day are provided for autos (Table A-A-1), pedestrians (Table A-A-2) and bicycle (Table A-A-3) in Appendix A. This data was used to generate a hypothetical origin-destination matrix (Table A-A-4), also included in Appendix A.

As of June 2021, all links (pavement, sidewalks, and bicycle facilities) are assumed to be in reasonable condition. Pavement condition data is included in Appendix B as **Error! Reference source not found.** (DelDOT roads) and **Error! Reference source not found.** (City of Newark streets).

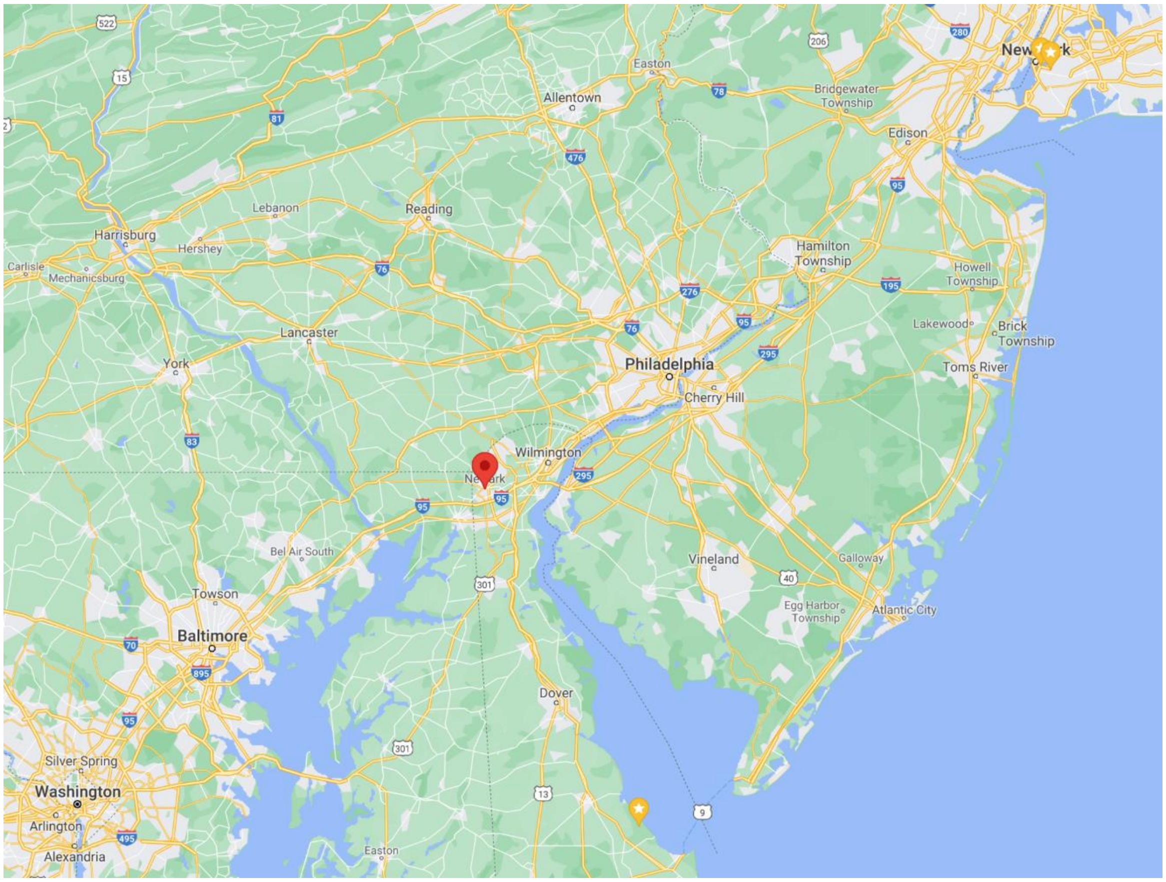

Figure 4-1. Location of Newark, Delaware (Google Maps, 2021)

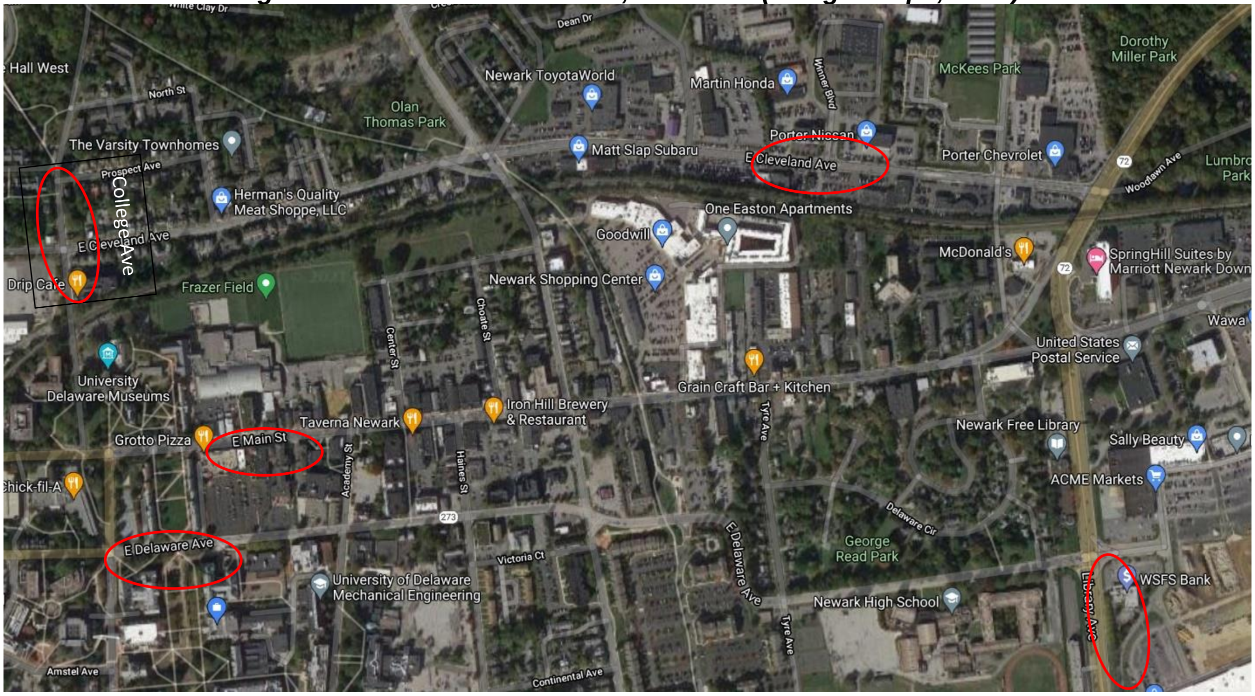

Figure 4-2 Study Area (Google Earth, 2021)

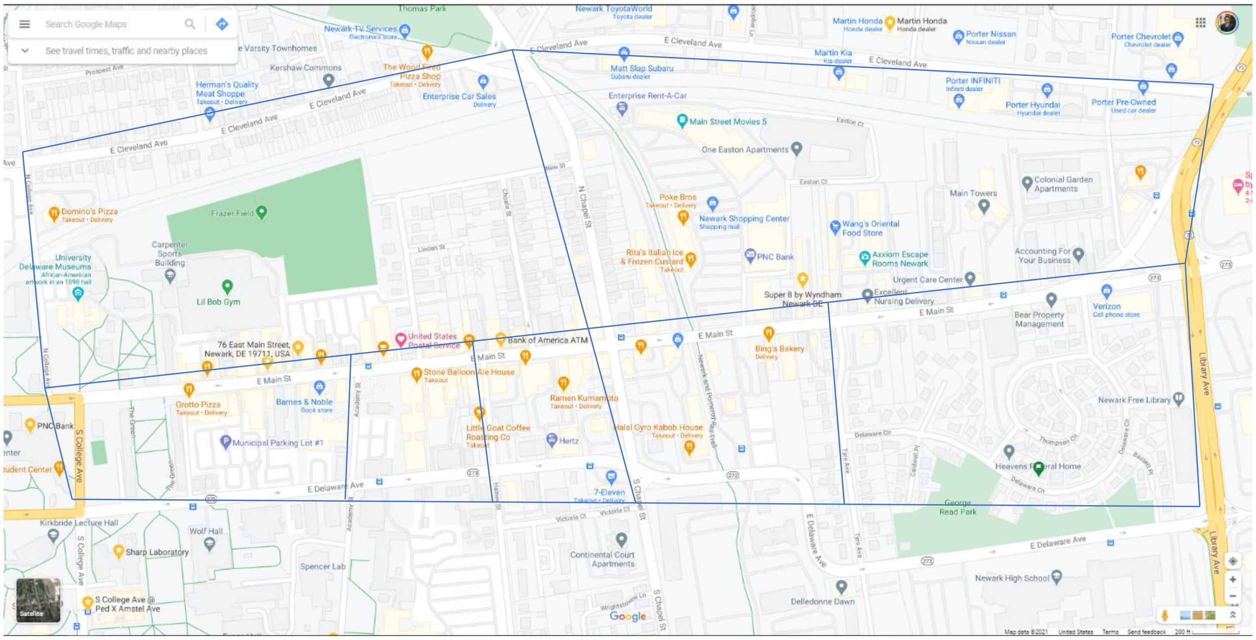

Figure 4-3. Network Representation of Study Area

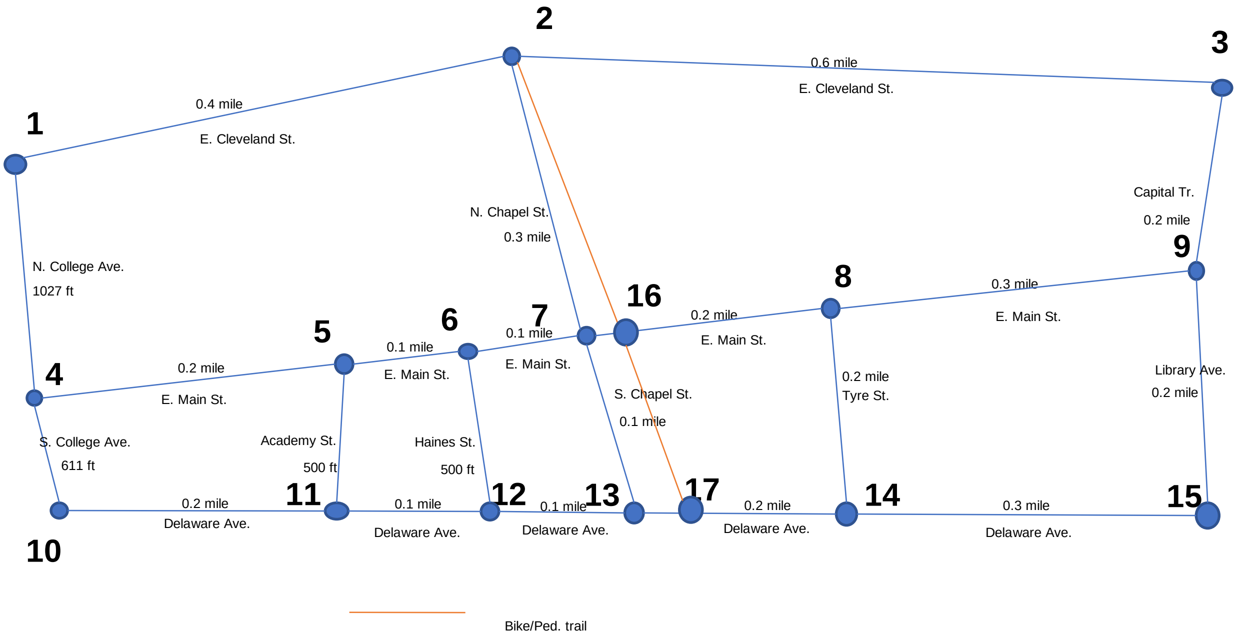

Figure 4-4 Labeled Network for the Study Area

Table 4-9 Link Attributes

	Street name	Car		Bike		Pedestrian		On street parking	
Link		# lane	Direction	Type	Width	Width	Sides	Yes/ No	Sides
1-2	E. Cleveland St.	1	2	Mixed	Null	4	2	No	
1-4	N. College Ave.	1	2	Bike lane	2’	4	2	Yes	1
2-3	E. Cleveland St.	1	2	Bike lane	2’	4	2	No	
2-7	N. Chapel St.	1	2	Mixed	Null	4	2	Yes	1
2-17*	Pomeroy Trail			Trail	10				
3-9	Capital Tr.	3	2	Mixed	Null	4	2	No	
4-9*	E. Main St.	2	1 (WB)	Sharrow	Null	4	2	Yes	2
4-10	S. College Ave.	1	2	Bike lane	5’	4	2	Yes	1
5-11	Academy St.	1	2	Mixed	Null	4	2	Yes	1
6-12	Haines St.	1	2	Mixed	Null	4	2	Yes	1
7-13	S. Chapel St.	1	2	Mixed	Null	4	2	Yes	1
8-14	Tyre Ave.	1	2	Mixed	Null	3.5’	2	Yes	2
9-15	Library Ave.	2	2	Mixed	Null	4	2	No	
10-15*	Delaware Ave.	2	1 (EB)	Bike lane	5’	4	2/1	No	

*2-17 includes links 2-16 and 16-17; 4-9 includes links 4-5, 5-6, 6-7, 7-16,16-8, 8-9; 10-15 includes 10-11, 11-12, 12-13, 13-17, 17-14 and 14-15.

Table 4-10 Link Walkability and Bikeabilty (from walkscore.com)

Link	Street name	Walk Score (Numerical)	Walk Score (Qualitative)	Bike Score (Numerical)	Bike Score (Qualitative)
1-2	E. Cleveland St.	71	Very Walkable	84	Very Bikeable
1-4	N. College Ave.	77	Very Walkable	84	Very Bikeable
2-3	E. Cleveland St.	66	Somewhat Walkable	71	Very Bikeable
2-7	N. Chapel St.	83	Very Walkable	85	Very Bikeable
2-16	Pomeroy Trail	85	Very Walkable	93	Biker’s Paradise
3-9	Capital Tr.	66	Somewhat Walkable	71	Very Bikeable
4-5	E. Main St.	86	Very Walkable	85	Very Bikeable
4-10	S. College Ave.	83	Very Walkable	78	Very Bikeable
5-6	E. Main St.	86	Very Walkable	85	Very Bikeable
5-11	Academy St.	85	Very Walkable	86	Very Bikeable
6-7	E. Main St.	86	Very Walkable	85	Very Bikeable
6-12	Haines St.	85	Very Walkable	94	Biker’s Paradise
7-13	S. Chapel St.	85	Very Walkable	96	Biker’s Paradise
7-16	E. Main St.	86	Very Walkable	85	Very Bikeable
8-9	E. Main St.	86	Very Walkable	93	Biker’s Paradise
8-14	Tyre Ave.	85	Very Walkable	98	Biker’s Paradise
8-16	E. Main St.	86	Very Walkable	93	Biker’s Paradise
9-15	Library Ave.	66	Somewhat Walkable	71	Very Bikeable
10-11	Delaware Ave.	85	Very Walkable	94	Biker’s Paradise
11-12	Delaware Ave.	85	Very Walkable	94	Biker’s Paradise
12-13	Delaware Ave.	85	Very Walkable	94	Biker’s Paradise
13-17	Delaware Ave.	85	Very Walkable	94	Biker’s Paradise
14-15	Delaware Ave.	85	Very Walkable	94	Biker’s Paradise
14-17	Delaware Ave.	85	Very Walkable	94	Biker’s Paradise
16-17	Pomeroy Trail	85	Very Walkable	93	Biker’s Paradise

ANTICIPATED CHALLENGES AND EXPECTED RESULTS

To explore whether consideration of disruptions to all modes is important some preliminary analysis was conducted. The analysis computed the impact of a recent roadway reconstruction of three links of the 50-link network. Anecdotal evidentce suggested that the reconstruction of these three links had significant impacts on all three modes (auto, bicycle and pedestrian). Of those impacted users, travel times for automobiles and bicycles increased by about 6%. Travel times for pedestrians increased from between 12 and 23% depending on how the user navigated around the construction (moving to a different side of the street or taking an alternative route). Additionally, non-motorized modes experience 22% of the total delay, but are only 5.5% of the users. This disruption is critical when looking at planning, scheduling, and implementing maintenance activities from the perspective of different user groups, such as the mobility-impaired or commuters versus recreational users.

To capture this, we plan to build on the existing literature on transportation project optimization/prioritization and performance measures for roadways, sidewalks, and bikeways, capturing the roadway user, pedestrian, and cyclist needs. The objectives and constraints of this project recognize the user needs (safety, travel time reliability, bikeability and walkability, desired LOS), agency needs (available funds, activity durations, available equipment, project quality), environmental sustainability (CO2 emission) and social sustainability (equity, accessibility, and mobility).

A clustering algorithm (K-means, hieratical clustering, or other machine learning algorithms) is presented in Chapter 6 that bundles (optimize/sequence) maintenance activities considering multiple objectives. Trade-off analysis is conducted using different objectives for bundling using an algorithm develop to create the bundles and code developed to evaluate each bundle. Drawing on the concepts explored in this chapter, this analysis in Chapter 6 aims to provide practical recommendations for sequencing the roadway, sidewalk, and bikeway activities to maximize the pre-determined objectives. The trade-off analysis also helps to identify the key factors that impact the achievement of the objectives.

Some of the challenges we found include dealing with the different spatial and temporal scales. Unacceptable distress levels, physical barriers, poorly timed traffic signals, or poor pavement markets can disrupt a pedestrian or bicycle trip at any time, but maintenance may only be undertaken once per year. Alternative paths are dependent on safe intersections that may not be timed to cater to non-motorized users.

Furthermore, the additional analysis helps to provide a sense of the order magnitude of disruptions and the key factors that influence performance that may serve as a foundation for future guidelines suitable for local governments that most commonly manage these facilities.

CONCLUSIONS

Performance measures, such as travel time, capture the physical relationships in the sociotechnical system, identifying different classes of users and capturing some of the functional relationships. Intentional and normative relationships can be captured as constraints on accessibility or due to regulations.

Some of the challenges include dealing with the different spatial and temporal scales. Unacceptable distress levels, physical barriers, poorly timed traffic signals, or poor pavement markings can disrupt a pedestrian or bicycle trip at any time, but maintenance may only be undertaken once per year. Alternative paths are dependent on safe intersections that may not be timed to cater to non-motorized users.

This effort provided a sense of the order of magnitude of disruptions and the key factors that influence performance to be able to assemble guidelines suitable for local governments that most commonly manage these facilities.

In summary, non-motorized modes of transportation are important, but go largely ignored. In our investigation of the impacts on users of maintenance of a real network, pedestrians and bicyclists were found to be disproportionately disadvantaged. Using the perspective of a socio-technical system, performance measures in this work offer a means for capturing these differences and are useful for building tools to support those who wish to consider these users in maintenance planning.

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CHAPTER 5

Modeling the Enhanced Network

INPUT DATA

The original sketch network contains only 17 nodes, and the mode of each arc in the sketch network is not specified. To facilitate the evaluation, a detailed multi-modal network that considering the intersections, crosswalk, mode transfer facilities should be constructed. Thus, a much more detailed multi-modal network is constructed accordingly, using the following information:

- The original sketch network,
- GIS data of roadways, sideways, intersections, and crosswalks (DE DOT),
- Detailed layout of the component of the network in GoogleEarth (earth.google.com),
- The parking information (newarkde.gov),
- The bike lane information (BikeNewark.org),
- DEM data of 1m resolution (apps.nationalmap.gov)

The detailed layout in GoogleEarth, the parking information, the bike lane information and DEM and example of a road elevation profile is provided in Appendix C.

GEODATA PROCESSING

The modes of this multi-modal network include automobile, cyclist, pedestrian, and transfer. Specially, the cross walks at intersections and cross walk between intersections are modeled as arcs with mode of pedestrian. The transfer facility, such as the parking lots and on street parking spots for transfer between automobile and pedestrian, together with the bike parking spots for transfer between cyclist and pedestrian, are modeled as arcs with mode of transfer. Then, the GIS shapefile for the multi-modal network is constructed by semi-automated approach using the QGIS software. Specially, the direction of each bike lane and automobile lane is assigned according to the input data. Then the graph network data as an adjacent matrix is generated with python codes and some geographic extensions (e.g., geopandas). If a link is bi-directional, then both the link and its mirror is included in the adjacent matrix. Besides the adjacent matrix of the graph for the multi-modal network, for each arc in the network, some additional attributes and parameters are calculated in the next section.

NETWORK ATTRIBUTES CALCULATION

To facilitate a travel time calculation in a multi-modal network, the mode, vertical topography, horizontal topography attributes, and parameters for travel time considering congestion effects are calculated.

Mode

The mode of each arc is assigned according to the information in the GIS data of roadways, sideways, intersections, and crosswalks. Additionally, GoogleEarth software is used to check the corrected mode of each arc.

Vertical Topography

The vertical topography information such as Maximum Gradients and maximum elevation difference is calculated through the 3D analysis in the QGIS with DEM data. The maximum gradient of an arc is calculated according to the elevation profile of the arc generated from the DEM data. Additionally, the maximum elevation difference is also calculated using such elevation profile.

Horizontal Topography

The physical length is calculated in the QGIS by directly extracting the length from the shapefile, and the free travel time is calculated according to the length and other attributes such as intersection, crosswalk, and gradient. The length of each arc (L_a) is used for free travel time calculation of normal automobile, cyclist, and pedestrian arcs. The length of transfer arc is not used for travel time calculation. Instead, a fixed travel time is assigned to this type of arcs. The free flow travel speed for the common travel arcs and fixed transfer time for transfer arcs is listed in Table 5-1 Parameters for Free Flow Travel Time CalculationTable 5-1.

Table 5-1 Parameters for Free Flow Travel Time Calculation

Free Speed (v_a^m) (mph)			Transfer time ($t_a^{m_1,m_2}$) (minute)			
Automobile	cyclist	pedestrian	automobile-cyclist	automobile-pedestrian	cyclist-pedestrian	
25	9.4	3.1	4	4	2	

For the arc that shared between the automobile and cyclist in a "sharrow" style, the free travel speed of the automobile is set same as the cyclist. For pedestrian and cyclist to climb up the elevation along the arc, it is assumed that ascending speed is 0.1minute/m. For an automobile arc, the free travel time (in minutes) of length L_a is calculated as shown in Eqn 5-1:

$$t_a^{au} = L_a/v_a^{au} \tag{5-1}$$

For a common pedestrian arc with the maximum elevation difference of Za, the free travel time (in minutes) is calculated as shown in Eqn 5-2:

$$t_a^{pe} = \frac{L_a}{v_a^{pe}} + Z_a/10 \tag{5-2}$$

For a common cyclist arc with the maximum elevation difference of Za, the free travel time (in minutes) is calculated as shown in Eqn 5-3:

$$t_a^{cy} = \frac{L_a}{v_a^{cy}} + Z_a/10 \tag{5-3}$$

Specially, for free travel time of crosswalk at intersection, 1 minute is added to the free travel time calculated by previous equations, with respect to the additional waiting times at intersections.

Parameters for Travel Time Calculation in Congestion

A BPR function is used for travel time calculation for automobile arcs that considering the congestion effects. The parameters for BPR functions are listed in Table 5-2.

Table 5-2 BPR Parameters

Parameter	α	β	Capacity (veh/ln/hr)
Arterial	0.6	5	1600
Local Street	0.5	1	1200

NETWORK REPRESENTATION

The network used for the analysis is shown in Figure 5-1. This network differentiates the link and node attributes among the different modes

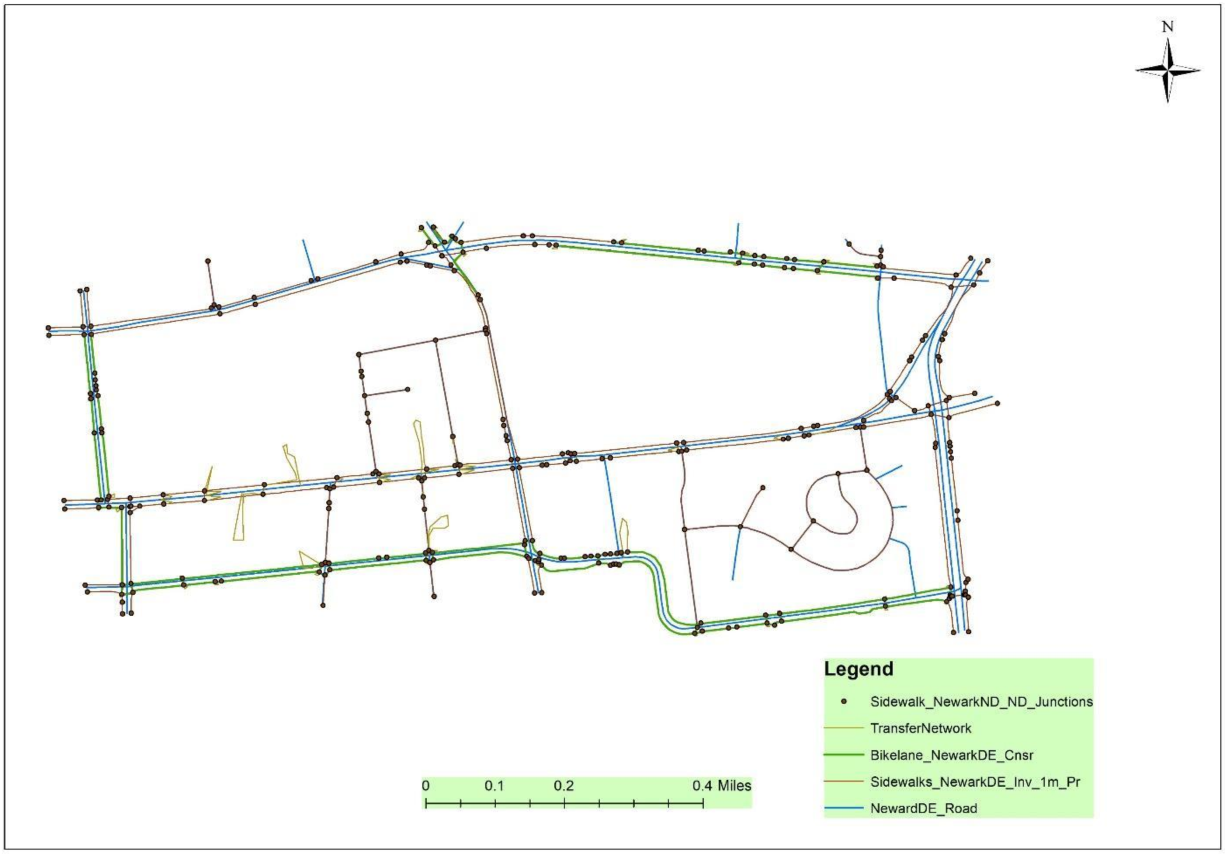

Figure 5-1 Layout of Multi-Modal Network in GIS

PATH TRAVEL TIME CALCULATION

According to the O-D demand data, the O-D demands of pedestrian and cyclist is in single digits which are much less than the capacity of the corresponding arcs, and the O-D demands for the automobile are relatively high. However, for a practical traffic assignment, an all-or-nothing (AoN) method is good enough for all three modes of demand at current stage. For a single mode network assignment, the conventional Bellman-Ford shortest path algorithm (Bellman, 1958; Ford Jr, 1956) is used. For a shortest path calculation in a multi-modal network that considering the viability of paths combing more than one modes, the viable shortest path algorithm developed by (Lozano & Storchi, 2001) can be used.

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CHAPTER 6

Multi-Modal Transportation Infrastructure Project Bundling

BACKGROUND AND INTRODUCTION

Transportation infrastructure elements are usually managed independently by asset type. However, for transportation elements in the same corridor, the maintenance, rehabilitation, and improvement activities on one element can affect other elements because they are interconnected. For example, a pavement reconstruction activity could cause a closure of bikeways and sidewalks in the same direction and disrupts the bicyclists and pedestrians. Thus, arranging maintenance, rehabilitation, and improvement activities independently solely based on their own asset type may incur unanticipated impacts on other asset types, especially for the users. Transportation infrastructure project bundling has been found to have advantages of reducing total cost, improving efficiency, and reducing automobile user delay costs. However, in past research, the major focus of transportation infrastructure project bundling was placed on finding similarities of the projects, examining the overall economic impact, and investigating the time-cost trade-off of different bundling strategies. Little literature was focused on the project bundle's impact on different roadway users (pedestrians, bicyclists, automobile drivers, etc.) and the trade-off analysis among the impacts on different users that may occur, particularly in business districts and other mixed use areas. The objective of this project is to bundle 50 anticipated pavement, sidewalk, and bikeway projects over 10 years and investigate the trade-offs among increased travel times of three mode users, standard deviations of increased annual travel times of the three mode users, and cost. In this project, the research transportation system is located in the business district of Newark, Delaware. Three asset types (pavements, bikeways, and sidewalks) and three corresponding modes (automobile, bicycle, and walk) in this area will be considered. The original maintenance, rehabilitation, and improvement schedule of three asset types were determined separately with a planning horizon of 10 years. The aforementioned objectives were compared between the original project implementation plan and the bundled project implementation plan.

LITERATURE REVIEW

Transportation infrastructure project bundling typically aims to cluster projects with similar features (material type, condition ratings, traffic loading, maintenance history, geological proximity, etc.) and which, therefore, can be subject to application of the same treatment so as to save cost and improve efficiency (Shrestha et al., 2022). Bordat et al. (2004) asserted that projects that share the same work category and are geologically adjacent can be bundled together to reduce overall cost. It was identified that due to the variabilities in traffic conditions, the pavement segment condition rating may vary as well (Li et al., 2018; Qiao et al., 2018; Yang et al., 2009). Therefore. Yang et al. (2009) and Tsai et al. (2006) utilized the fuzzy c-means algorithm to select the optimal project termini that can minimize the rating change in the same bundle. Yang et al. (2009) found that by increasing the number of clusters and minimizing the rating variability, the maintenance cost can be reduced and therefore result in a reduction in total cost. However, if introducing too many clusters, the setup cost goes up significantly and increases the total cost. Alikhani and Jeong (2021) adopted k-means for highway project bundling based on 730 historical data records. The k-means method has been tested efficiently when facing a large database or multiple pavement condition-related factors. The results from k-means surpassed the performance of existing classification approaches using project work type.

For pavement management purposes and data collection, a single roadway is usually divided into shorter segments due to the differences in material, deterioration rate, and distress. Wang, Tsai, and Li (2011) stated that most of the prior research was focused on determining the treatment activities and their cost at the segment level without considering the special relationships of the segments. The authors further indicated that in real applications, adjacent sections are usually aggregated into a large M&R project and the best treatment alternative is applied to the segments in that aggregated project. Wang, Tsai, and Li (2011) proposed a topological ordering-based segment bundling algorithm to minimize the maintenance cost and set-up costs. In order to facilitate M&R work with lower costs, Lea (2015) proposed a method for grouping or merging small pavement segments into larger segments. In this method, the similarity of the original treatments, the proximity of the treatments, and the implementation time difference of the treatments were considered. The proposed method was applied to the entire Caltrans highway network and has been shown to be efficient with reasonable results. Considering the specialized, uncapacitated facility location problem (UFLP) from operation research, Qiao et al. (2019) investigated the impact of project bundling on the Maintenance of Traffic (MOT) cost. Logistic regression was carried out on data with 36 project types and six work categories. Several major contributors to the MOT cost were identified, including project vicinity, traffic conditions, bundle size, etc. However, it was discovered that the effects of these contributors to MOT cost differed greatly according to the type of project.

There are a few works focused on overall economies of scale and economies of competition brought by project bundling. Estache and Iimi (2011) indicated that bundling small contracts into larger contracts can lead to economies of scale but may also cause less competition and increase the unit cost. The same result was concluded by (Li et al., 2018; Qiao et al., 2018; Yang et al., 2009). Moreover, Li et al. (2018) and Qiao et al. (2018) investigated the effect of project bundling for six project categories: utility, bridge, traffic, structure, miscellaneous work, and road work projects. It was found that the higher the similarity of the projects in the same bundle, the less the total contract cost. This effect is most obvious for road work projects. A reduction in MOT cost through project bundling was observed for all project categories.

Mungle et al. (2013) proposed a fuzzy clustering-based genetic algorithm (FCGA) to generate Pareto fronts and further examine the trade-offs between cost, duration, and quality of different highway project bundling scenarios. Most literature on time–cost–quality or time-cost trade-off analysis for construction projects is focused on project scheduling or resource allocation rather than bundling (Jaafar, Bin, Uddin, & Najjar, 2016; Lotfi et al., 2022; Luong, Tran, & Nguyen, 2021; Tavassoli et al., 2021). Miralinaghi et al. (2022) considered both project scheduling and bundling to minimize the total project costs and user delay costs (vehicle travel time). The authors used a bi-level programming method to formulate the problem and solved using a non-dominated sorting genetic algorithm (NSGA-II).

In the research examined, the major effort of transportation infrastructure project bundling was laid on finding similarities of the projects, examining the overall economic impact, and investigating the time-cost trade-off of different bundling strategies. However, little literature was focused on the project bundles' impact on various travel modes or the trade-off analysis among the impacts on different types of users.

INTRODUCTION TO THE STUDY AREA

The study area is located in the business district of Newark, Delaware. Newark is home to the University of Delaware and is located just off I-95 between New York City and Washington DC. The selected study assets are roads, sidewalks, and bicycle paths bounded by East Cleveland Ave on the north, Delaware Ave on the south, Library Ave on the east, and College Ave on the west. Main Street is the major east-west road and the commercial center of town. Main Street is one-way westbound and Delaware Ave to the south is one-way eastbound. The simplified and labeled network is shown in Figure 6-1. In this study area, most of the bikeways are shared with automobile traffic. North College Ave, East Cleveland Street, South College Ave, and Delaware Ave have 2- to 5-ft-wide bike lanes. Link 2-7 is a pedestrian and bike trail with a width of 10 feet. The roadway attributes are provided in Table 4-9.

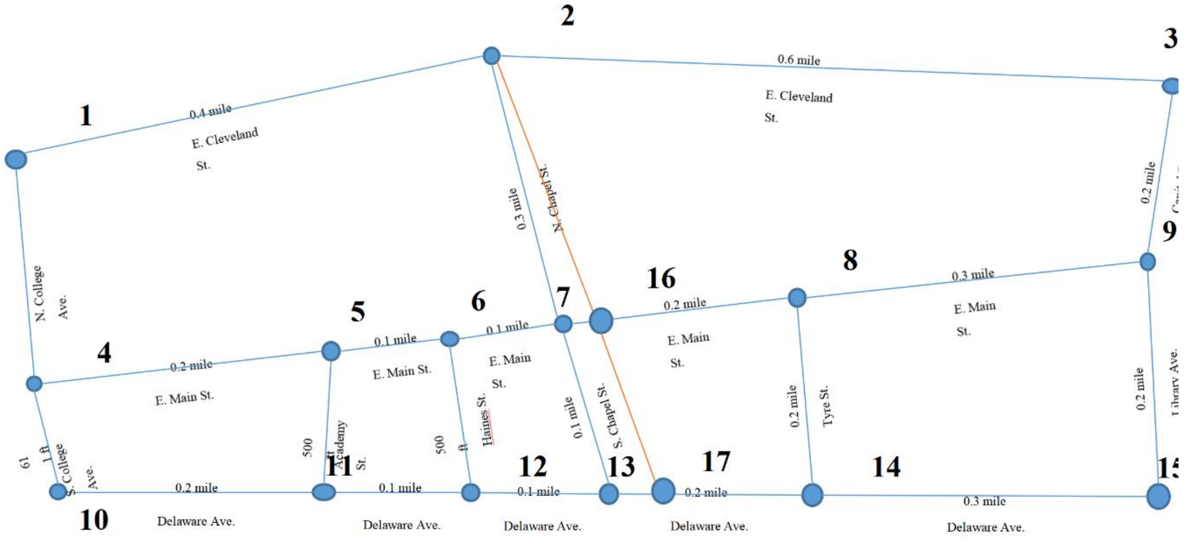

Figure 6-1 Simplified and Labeled Network for the Study Area

In this study area, a pavement maintenance and rehabilitation schedule with a planning horizon of 10 years was adopted from (Abdallah et al., 2021). The walk score and bike score of each road (from walkscore.com) are summarized in Table 4-10. Estimated realistic peak hour Origin-Destination (O-D) demands for the three modes (vehicle, bicycle, pedestrian) are summarized in 0. Daily O-D demand is assumed as 12.5 times the peak hour O-D demand (FHWA, 2018). Sidewalks and bikeways with walk scores or bike scores below 80 will be reconstructed once in the planning horizon while the implementation time of reconstruction remained undecided. For more flexible project implementation possibilities, each road has been further divided by link and traffic direction. Each project is represented by a project index that denotes one action in one traffic direction on that link. As a result, there are 50 projects in total that contain 5 action categories as summarized in Table 6-1. The construction cost and construction duration of each project are derived from Virginia Department of Transportation documents (Virginia Department of Transportation; Virginia Department of Transportation) and (Aoun, 2013). The details of estimated construction costs, estimated construction durations, and the specific projects that each project index represents are provided in Appendix D (**Error! Reference source not found.**). Mobilization costs and durations are usually project-specific. However, for simplicity, mobilization costs and durations were fixed for each action category in this study. The mobilization costs and durations are estimated based on the analysis in (Virginia Department of Transportation, 2017). The mobilization costs and durations are summarized in Table 6-2.

Table 6-1 A Summary of Projects in the Study Area.

Action Category	Asset	Number of Projects
Reconstruction 1	Pavement	8
Major repair	Pavement	16
Minor repair	Pavement	12
Reconstruction 2	Sidewalk	10
Reconstruction 3	Bikeway	4

Table 6-2 Mobilization Cost and Duration for Five Action Categories.

Action Category	Asset	Mobilization Cost (USD)	Mobilization Duration (days)
Reconstruction 1	Pavement	80, 000	5
Major repair	Pavement	40, 000	4
Minor repair	Pavement	20, 000	4
Reconstruction 2	Sidewalk	20, 000	4
Reconstruction 3	Bikeway	20, 000	3

This study aims to bundle 50 projects into the 10-year planning horizon and examine the effect of different bundling plans on the travel time of three modes of users and total agency costs. Effects on infrastructure deterioration due to varying project timing within the 10-year horizon were not considered in this initial study. It is assumed that the agencies only have one set of equipment for each action category, which means no simultaneous projects from the same action category are possible. Mobilization cost/duration will be counted only once for projects in the same year, on the same street, and belonging to the same action category. The travel time of users in each of the three modes is evaluated independently; it is assumed that there is no mode transfer. For each mode, the conventional Bellman-Ford shortest path algorithm (Bellman, 1958; Ford Jr, 1956) is used. Details of the applied shortest path algorithm can be found in Chapter 5. The notations for this study are as follows:

B	maximum annual construction budget
M	total number of action categories
N	total number of projects
Y	planning horizon (years)
$aveta$	average annual increased travel time for automobile users over the planning horizon
$aveta^{jk}$	average increased travel time per day for automobile users caused by action category k in year j
$avetb$	average annual increased travel time for bicyclists over the planning horizon
$avetb^{jk}$	average increased travel time per day for bicyclists caused by action category k in year j
$avetp$	average annual increased travel time for pedestrians over the planning horizon
$avetp^{jk}$	average increased travel time per day for pedestrians caused by action category k in year j
c_i	construction cost (USD) of implementing project i
d_i	construction duration (days) of implementing project i
$mcac^k$	mobilization cost of action category k
$mdac^k$	mobilization duration of action category k
nm^{jk}	number of mobilizations of action category k in year j
ta_i	increased travel time per day for automobile users when implementing project i and only considering construction
ta^j	increased travel time for automobile users in year j caused by construction
tb_i	increased travel time per day for bicyclists when implementing project i and only considering construction
tb^j	increased travel time for bicyclists in year j caused by construction
tp_i	increased travel time per day for pedestrians when implementing project i and only considering construction
tp^j	increased travel time for pedestrians in year j caused by construction
x_i^j	1 if project i is assigned to year j; 0 otherwise.
yta^j	total increased travel time for automobile users in year j
ytb^j	total increased travel time for bicyclists in year j
ytp^j	total increased travel time for pedestrians in year j

PROBLEM FORMULATION

In this section, the project bundling problem is formulated as a multi-objective multidimensional knapsack problem (MOMKP). The conventional formulation of the MOMKP can be found in (Thibaut & Teghem, 2012). In this study, each project index sequence consists of 10 knapsacks representing the 10-year planning horizon. Each knapsack contains a list of project indices indicating which project should be done in which year. A maximum annual construction budget of 0.55 million USD is applied each year. Each bundling plan is obtained after assigning the project index sequence into 10 knapsacks (years). The order of the project index in the project index sequence is important since it states the order of implementation projects on the planning horizon.

In this project bundling problem, all the projects will be implemented on the planning horizon while in most MOMKP formulations, only several items will be selected from a pool. The proposed MOMKP for project bundling is formulated as follows:

$$\min\ (\varphi_1(c),\ \varphi_2(ta), \varphi_3(tp), \varphi_4(tb), \varphi_5(sdta), \varphi_6(sdtp), \varphi_7(sdtb)) \tag{6-1}$$

$$\varphi_1(c) = \sum_{j=1}^{Y}\sum_{i=1}^{N} c_i x_i^j + \sum_{j=1}^{Y}\sum_{k=1}^{M} nm^{jk} mcac^k \tag{6-2}$$

$$\varphi_2(ta) = \sum_{j=1}^{Y}\sum_{i=1}^{N} ta_i d_i x_i^j + \sum_{j=1}^{Y}\sum_{k=1}^{M} nm^{jk} mdac^k aveta^{jk} \tag{6-3}$$

$$\varphi_3(tp)\ = \textstyle\sum_{j=1}^{Y}\sum_{i=1}^{N} tp_i d_i x_i^j + \sum_{j=1}^{Y}\sum_{k=1}^{M} nm^{jk} mdac^k avetp^{jk} \tag{6-4}$$

$$\varphi_4(tb)\ = \textstyle\sum_{j=1}^{Y}\sum_{i=1}^{N} tb_i d_i x_i^j + \sum_{j=1}^{Y}\sum_{k=1}^{M} m^{jk} mdac^k avetb^{jk}\ n \tag{6-5}$$

$$\varphi_5(sdta)\ = \sqrt{\frac{\sum_{j=1}^{Y}(yta^j - aveta)^2}{Y}} \tag{6-6}$$

$$\varphi_6(sdtp)\ = \sqrt{\frac{\sum_{j=1}^{Y}(ytp^j - avetp)^2}{Y}} \tag{6-7}$$

$$\varphi_7(sdtb)\ = \sqrt{\frac{\sum_{j=1}^{Y}\left(ytb^j - avetb\right)^2}{Y}} \tag{6-8}$$

Subject to

$$\textstyle\sum_{i=1}^{N}\sum_{j=1}^{Y} x_i^j\ = 1 \tag{6-9}$$

$$\textstyle\sum_{i=1}^{N} c_i x_i^j + \sum_{k=1}^{M} nm^{jk} mcac^k \le B^j, \qquad j = 1,2,\dots,Y \tag{6-10}$$

Objective function (6-2) includes the total construction cost and total mobilization cost over the planning horizon by following a specific bundling plan. Objective functions (6-3) to (6-5) calculate the total increased travel times for the three modes of users. Objective functions (6-6) to (6-8) specify the standard deviation of annually increased travel times for three mode users in the planning horizon. Minimizing objectives (6-6)-(6-8) is important when policy makers don’t want to have a huge amount of impact on any of the three modes of users in one year. Constraint (6-9) denotes that each project will only be implemented once on the planning horizon. Constraint (6-10) states that the sum of construction cost and mobilization cost in a year cannot exceed the maximum construction budget limit for the year. However, in this study, the maximum construction budget is considered the same (0.55 million USD) for all years. By minimizing objectives (6-2)-(6-8) under constraints (6-9)-(6-10), we aim to investigate possible project bundling plans that can minimize the total cost of implementing all projects, minimize the impact on the increased travel times for three mode users, and seek to evenly distribute the impact on the increased travel times over the planning horizon.

SOLUTION METHOD

Solutions to the knapsack problems and their variants can be classified into three categories: exact methods, approximation methods, and heuristic methods. Among them, heuristic methods like genetic algorithms (GA) have been well studied, because they have relatively short computational times and can yield near-optimal solutions, especially when facing multiple objectives and large decision spaces. MOMKP is considered more difficult to solve than multi-dimensional knapsack problems (MKP) due to the multiple objectives introduced. Therefore, most of the solutions to the MOMKP in the literature are heuristic or hybrid methods. This study adopted the non-dominated sorting genetic algorithm II (NSGA-II) to solve the above-formulated project bundling problem. NSGA-II is one of the heuristic and evolutionary algorithms. It was first proposed by (Deb, Pratap, Agarwal, & Meyarivan, 2002) in a journal article. It has been widely applied to optimization problems such as transit scheduling problems (Chai & Liang, 2020; Chao & Xiaohong, 2013; Song, Ma, Guan, Liu, & Chen, 2012; J. Yang & Jiang, 2020), vehicle routing problems (Jemai, Zekri, & Mellouli, 2012; Jozefowiez, Semet, & Talbi, 2005; Mendes, Wanner, & Martins, 2016; Srivastava, Singh, & Mallipeddi, 2021), and the knapsack problem and its variants (Ishibuchi, Tsukamoto, & Nojima, 2009; Sato, Sato, & Miyakawa, 2019; Xie, Neumann, & Neumann, 2020). A comprehensive review of the NSGA-II and its applications on multi-objective optimization problems can be found in (Verma, Pant, & Snasel, 2021).

The framework of the proposed solution method for the project problem is presented in Figure 6-2. In the beginning, N project index sequences will be generated to serve as the initial population. Each project index sequence will be assigned to different years following the order in the sequence constrained by an annual construction budget. After assignment, those project index sequences turn into bundling plans and will be evaluated by objectives (6-2)-(6-8). After evaluation, if the termination criterion has not been met, the bundling plans in the current generation will be classified into Pareto fronts with ranks. The bundling plans on the same Pareto front will be sorted by the crowding distance, as explained in Population Selection. Bundling plans with high rank and large crowding distance will be selected to be the next generation population. There will be N bundling plans selected using the ranks and crowding distances. Those selected bundling plans will then become parents to crossover and mutate to generate offspring. The size of crossover and mutation offspring is N times the probability of crossover and mutation, respectively. The probability of crossover and mutation sums to 1. Therefore, there will be N offspring to be generated. Moreover, the offspring and the parent bundling plans will be combined to be the next generation population with a size of 2N. It should be noted that in the next generation, the project index sequences of the bundling plans in the pool should be reassigned into years to obtain new bundling plans. This is because, in the crossover and mutation steps, the sequence of projects has been changed, thus affecting the assignment results. After reassignment, the new bundling plans will be reevaluated by objectives (6-2)-(6-8). The steps will repeat until the termination criterion is met.

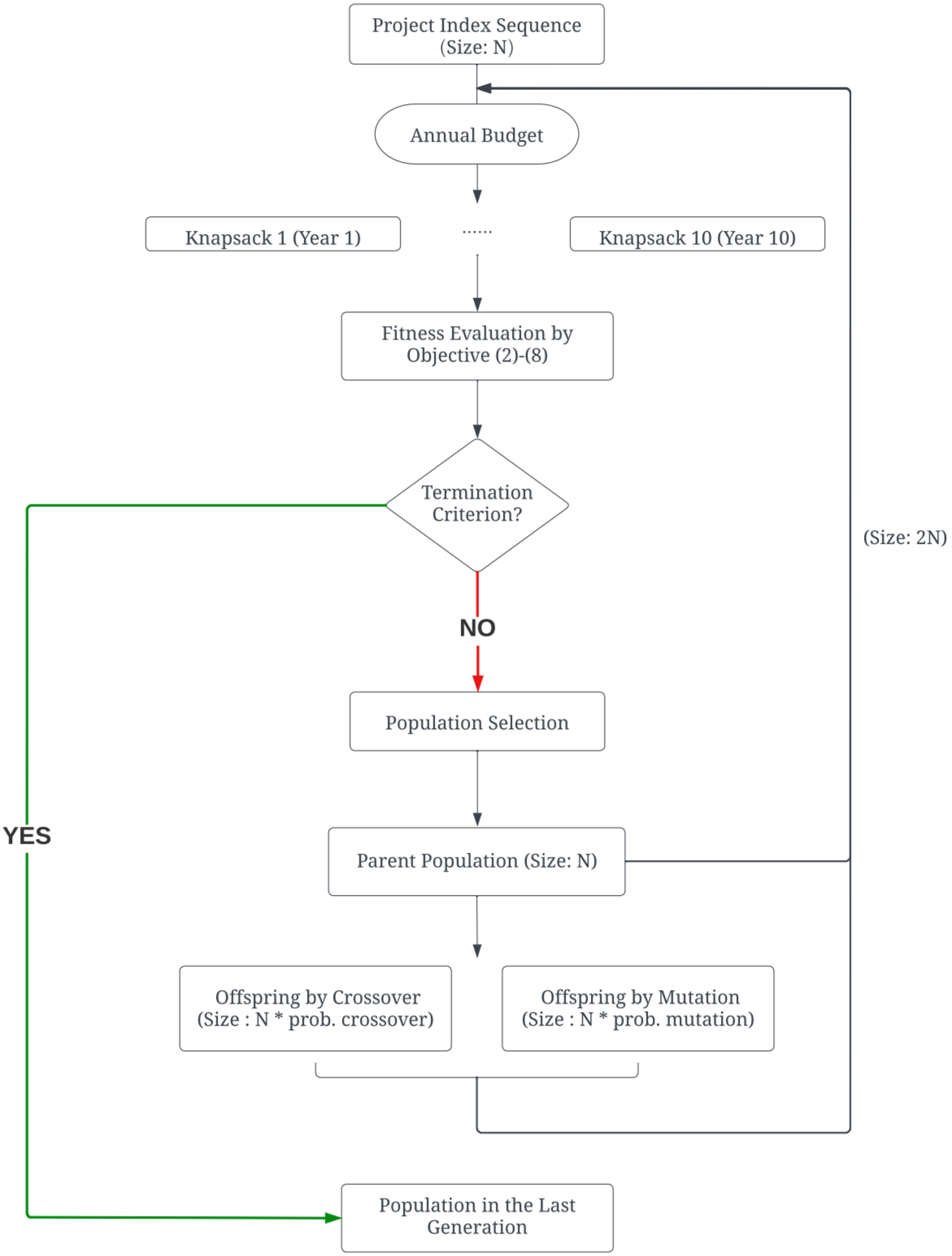

Figure 6-2 Proposed Solution Framework for the Project Bundling Problem.

Initial Population

The NSGA-II starts with generating the initial population to generate offspring. In this study, a pre-determined number of project index sequences are randomly generated to serve as the initial population. Each project index sequence specifies the order of implementing projects on the planning horizon. The specific projects that each project index represents can be found in Appendix D. The projects will then be assigned for 10 years to generate 10 knapsacks according to the order specified in the project index sequence with a maximum annual construction budget of 0.55 million USD. Once the maximum annual construction budget limit of the current year (current knapsack) is met, the current project will be assigned to the next year (next knapsack). Once the assignment process of a project index sequence is complete, we will obtain a bundling plan. The project indices in each year represent which specific projects should be done in the current year. An example of a project index assignment result is shown in Table 6-3. The initial project index sequence is [16, 13, …, 10, 26]. After the assignment, projects 16, 13, 19, 47, 11, 31, 14, and 42 were assigned into the first year (knapsack 1) with a total construction cost of 0.47 million USD. Project 9 has a construction cost of 0.15 million USD and thus was assigned for the next year (knapsack 2). The rest of the assignment process follows the same logic.

Table 6-3 An Example of Bundling Plan after Project Index Sequence Assignment

	Project index	Construction cost (USD)
Year 1 (knapsack 1)	[16, 13, 19, 47, 11, 31, 14, 42]	469,978
Year 2 (knapsack 2)	[9, 32, 45, 8, 4, 33]	531,357
Year 3 (knapsack 3)	[25, 48, 20, 27, 18, 30, 21]	345,486
Year 4 (knapsack 4)	[7]	510,714
Year 5 (knapsack 5)	[1, 41, 37, 0]	544,834
Year 6 (knapsack 6)	[23, 2, 38, 43, 46, 15]	386,308
Year 7 (knapsack 7)	[6]	510,714
Year 8 (knapsack 8)	[40, 3, 44, 5, 29]	399,867
Year 9 (knapsack 9)	[22, 35, 49, 34, 28, 36, 17]	515,913
Year 10 (knapsack 10)	[12, 39, 24, 10, 26]	339,471

Population Selection

The project selection happens after a population is generated. In project selection, the non-dominated sorting method is used to assign the population to Pareto fronts. The rank of each Pareto front is assigned as well. The bundling plan in the Pareto front with the highest rank will be selected first for the next generation population. After that, the bundling plan in the second highest rank Pareto front will be selected, until the size of the next generation population meets a pre-defined number. However, there is a probability that only a part of the bundling plan needs to be selected from a Pareto front to form a pre-defined number of the next-generation population. In such a case, crowding distance is adopted to measure the closeness of a bundling plan to its adjacent bundling plans in the same Pareto front. The crowding distance is an accumulative Euclidean distance over the objectives (6-2)-(6-8). The bundling plans with the largest crowding distance will be selected first to keep the diversity of the population. More details on the crowding distance be found in (Deb, Pratap, Agarwal, & Meyarivan, 2002).

Crossover, Mutation, and Replication

After population selection, NSGA-II will generate offspring to explore potential better bundling plans. In this study, the parent population will be combined with their offspring population to compete for the next generation population selection to avoid performance decay, thus replication is not considered. The reproduction process consists of two operations: crossover and mutation. One-point crossover is adopted, and the crossover point is the middle point of two-parent project index sequences. It could be highly likely that there are mutual project indices in the first half of parent 1 and the second half of parent 2, and vice versa. In such cases, the mutual project index will be preserved and passed to their offspring; only non-mutual project indices will crossover. The mutation operation also creates offspring with a probability. The mutation step does not happen after the crossover but along with the crossover. Crossover and mutation operations generate offspring independently. In this study, all projects need to be implemented and will only be implemented once on the planning horizon. Therefore, all projects are included in the project index sequence with no repetition. When mutating a project index sequence, the minimum number of mutation points is two, because a change in one project index must lead to a change in another project index in the sequence.

EXPERIMENTAL DETAILS

In this section, NSGA-II is applied to the study area in the business district of Newark, Delaware. Three asset types and three corresponding user travel modes are considered. Bikeway links are always closed when implementing pavement projects on the same street and in the same direction. For sidewalk links, two construction scenarios are considered. In scenario 1, both bikeway and pavement projects will not impact the travel time of pedestrians since all sidewalk links will remain open during bikeway and pavement projects and no mode transfer is happening. Whereas in scenario 2, there is no mode transfer as well, but the sidewalk links will be closed during adjacent pavement reconstruction and major repair projects.

The total trips of the three modes and the corresponding travel times for each of the three modes of users in the planning horizon without any projects are summarized in Table 6-4 and Table 6-5.

Table 6-4 Total Number of Trips for Three Modes in the Planning Horizon

	Automobile	Bike	Walking
Number of trips in 10 years (million)	709	17	16

Table 6-5 Cumulative Travel Time for Three Mode Users in the Planning Horizon without Projects

	Automobile users	Bicyclists	Pedestrians
Travel time (million minutes)	250	120	1404

In NSGA-II, the initial population size is determined as 40, namely 40 project index sequences will be generated initially. Those 40 project index sequences will turn into 40 project bundling plans after assignment. Since the parent population will be combined with their offspring for the next generation, the total number of project bundling plans in each population selection step is 80. Crossover is the main operation to generate offspring in NSGA-II. The probability of crossover and mutation are set as 0.7 and 0.3, respectively. The number of mutation points is fixed as 5. The NSGA-II ends after 700 generations. The experimental parameters are the same for both construction scenarios.

EXPERIMENTAL RESULTS

In this section, the NSGA-II is applied to the transportation network of the study area. Two scenarios are considered to compare and investigate the impact of pavement projects on pedestrian travel time. The relationships and trade-offs among the travel times, standard deviation of travel time, and agency cost are examined and discussed. The overall performance of the NSGA-II project bundling on the study network is also examined.

The Relationships and Trade-offs Among the Travel Time of the Three Modes

To investigate the effect of different bundling plans on the travel times of users of the three modes, the competitors in the last generation (generation 700) are extracted. The relationship between the cumulative increased travel times for two scenarios is presented in Figure 6-3 and Figure 6-4. The cumulative increased travel times are calculated using the following formula (6-1):

Cumulative increased travel time

= total travel time by following a project bundling plan – total travel time without projects (6-1)

As can be observed from Figure 6-3, the cumulative increased travel time of pedestrians does not change significantly with the automobile user and bicyclist cumulative increased travel times. However, the automobile user and bicyclist have positive relationships. Moreover, the change in bundling plans affects the automobile user travel time and bicyclist travel time in a similar way but not for the pedestrians. This is because the bike links are closed during pavement projects, so the travel time of bicyclists and automobile users is independent of pedestrians. Another reason for relatively stable cumulative increased pedestrian travel time under different bundling plans is that there are only 10 sidewalk projects that can affect the pedestrian travel time. In contrast, the automobile travel time can be affected by 36 pavement projects and the bicyclist travel time can be affected by 36 pavement projects and 4 bikeway projects.

Figure 6-4 shows that in scenario 2, pedestrian travel times have stronger positive relationships with automobile user travel time and bicyclist travel time. As anticipated, sidewalk link closure makes pedestrian travel time more dependent on the pavement projects and further relates to the bicyclist travel time.

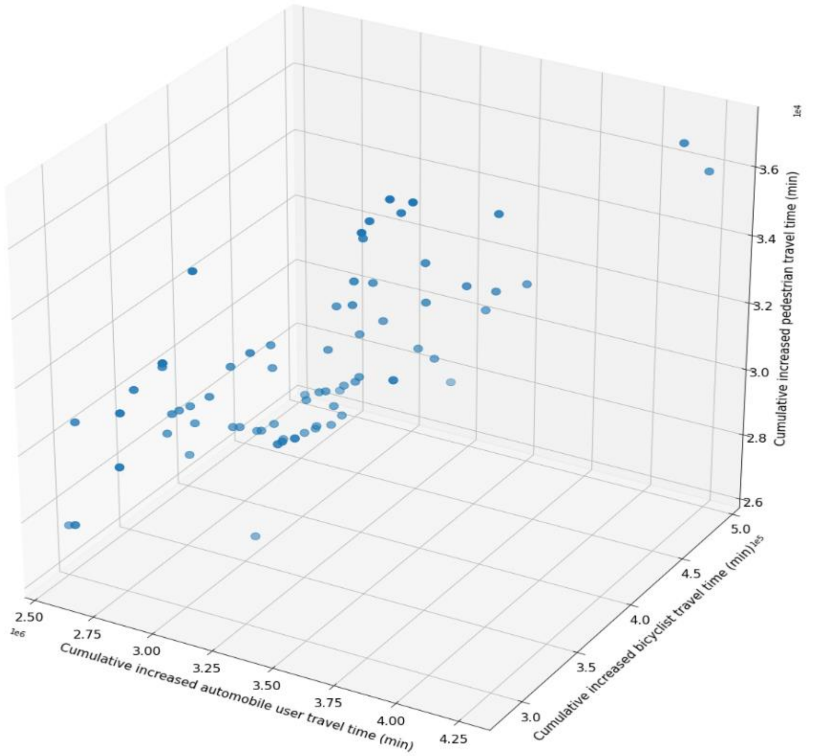

Figure 6-3 Cumulative Increased Bicyclist Travel Time versus Cumulative Increased Automobile User Travel Time versus Cumulative Increased Pedestrian Travel Time over 10 Years for Construction Scenario 1

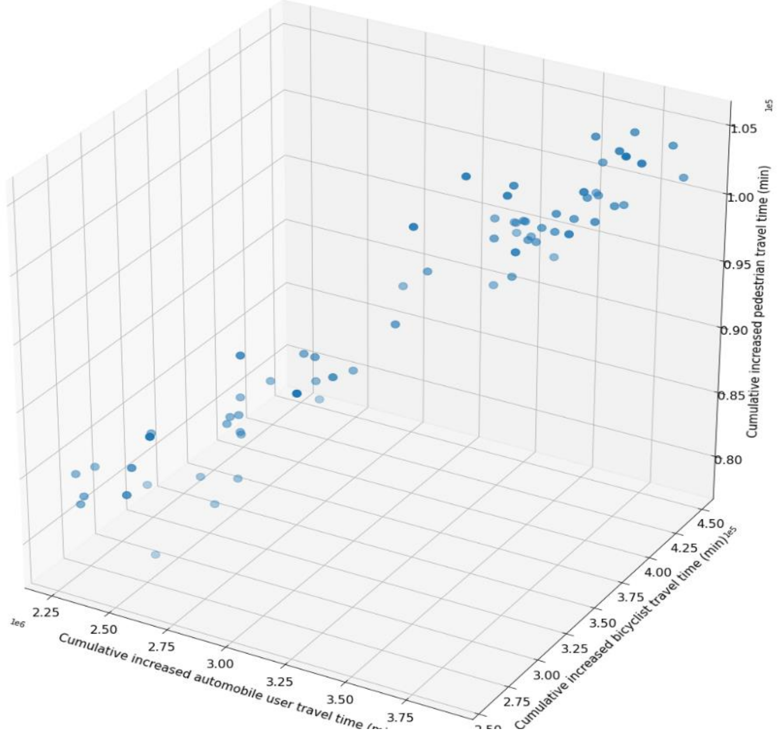

Figure 6-4 Cumulative Increased Bicyclist Travel Time versus Cumulative Increased Automobile User Travel Time versus Cumulative Increased Pedestrian Travel Time over 10 Years for Construction Scenario 2

Figure 6-3 and Figure 6-4 illustrate that the cumulative increased automobile user travel time is 10 to 100 times higher than that of the bicyclist and pedestrian. While, in Table 6-5, the automobile user travel time is much less than pedestrian travel time and is only two times as much as bicyclist travel time when no projects are implemented. This indicates that implementing the projects has caused more additional travel time for automobile users than pedestrians and bicyclists. This could be caused by: 1) the number of automobile trips over the planning horizon is more than 40 times as many as pedestrian and bicyclist trips, as shown in Table A-A-4; or 2) the implementation of the projects has caused more additional travel time per trip for the automobile user than the pedestrians and bicyclists. To examine the project bundle's impact on each trip, an alternate metric of cumulative increased travel time per use was considered using the following equation:

$$Cumulative\ increased\ travel\ time\ per\ use = \frac{Cumulative\ increased\ travel\ time\ in\ the\ planning\ horizon}{Total\ trips\ in\ the\ planning\ horizon}$$

As can be observed from Figure 6-5 and Figure 6-6, the increased travel time per use for automobile users is about the same as the pedestrian users and is about 30% of the bicyclist travel time. Therefore, it can be inferred that the large cumulative increased travel time of automobile users is caused by a large number of total trips.

In general, the two construction scenarios have little difference in the effect on the increased automobile user but have a significant effect on the pedestrian travel time per use, as can be seen from Figure 6-5. The average pedestrian travel time per use is increased from $1.8 * 10^{-3}$ to $6.1 * 10^{-3}$ (min/use). In scenario 1, the Pareto front shows that a 10^{-3} increase in increased automobile user travel time per use could result in a $2 * 10^{-4}$ decrease in increased pedestrian travel time per use. However, in scenario 2, the same amount of compromise made on the automobile user could yield a $4 * 10^{-4}$ decrease in increased pedestrian travel time per use. A similar observation can be seen in Figure 6-6. The increased bicyclist travel time per use does not have a large change in the two construction scenarios. In scenario 1, the Pareto front shows 10^{-3} increase in increased bicyclist travel time per use could lead to $5 * 10^{-5}$ decrease in increased pedestrian travel time per use. While the number increased to $3 * 10^{-4}$ in scenario 2. In other words, in scenario 2, the pedestrian travel time is more sensitive to the change in automobile user travel time and bicyclist travel time.

Figure 6-7 and Figure 6-8 illustrate that, in scenario 2, both increased automobile travel time per use and increased bicyclist time per use have a positive correlation with the increased pedestrian travel time per use. Moreover, in Figure 6-9, the increased automobile travel time per use is positively correlated with the increased bicyclist travel time per use in both scenarios. This explains why the increased automobile travel time and increased bicyclist travel time behave similarly under the two construction scenarios.

In summary, by examining the cumulative increased travel time per use of the three mode users, it can be concluded that the large cumulative increased travel time of automobile users is primarily caused by the large number of total trips. In scenario 1, the increased pedestrian travel time per use has little correlation with the increased automobile user travel time per use and increased bicyclist travel time per use. In scenario 2, increased time per use for all mode users is positively correlated. This holds true for cumulative increased travel times. Scenario 2 is considered to be more in accordance with real practice, so selecting a bundling plan that has good performance in either metric would have good performance in the remaining two performance metrics. In scenario 2, as logically anticipated, pedestrian travel time is more correlated to the change in automobile user travel time and bicyclist travel time.

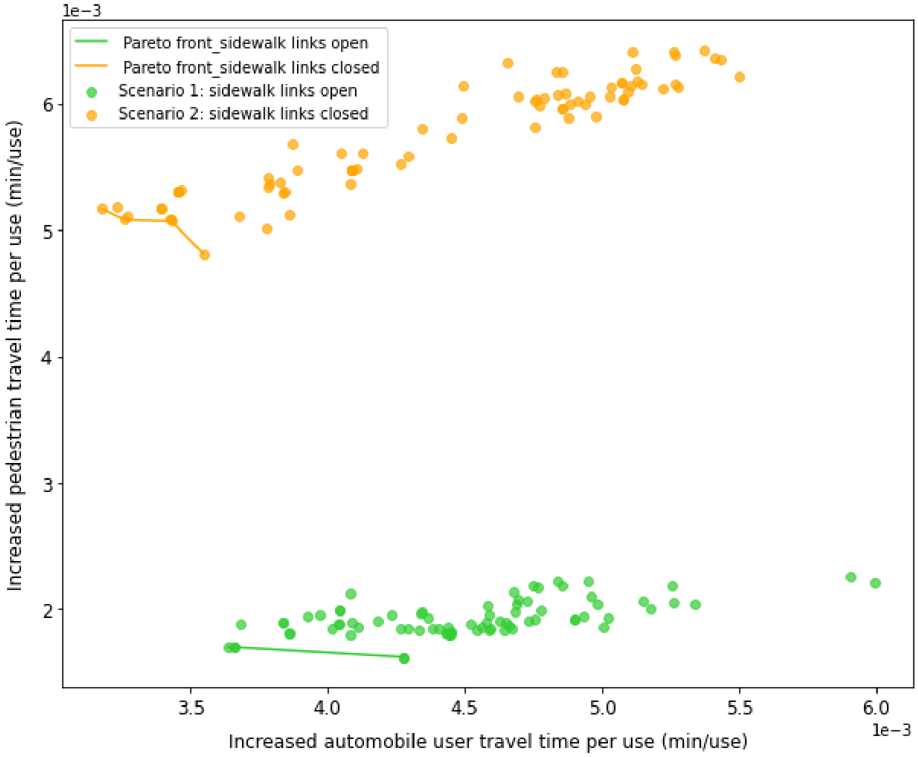

Figure 6-5 Increased Automobile User Travel Time per Use versus Increased Pedestrian Travel Time per Use for Two Construction Scenarios

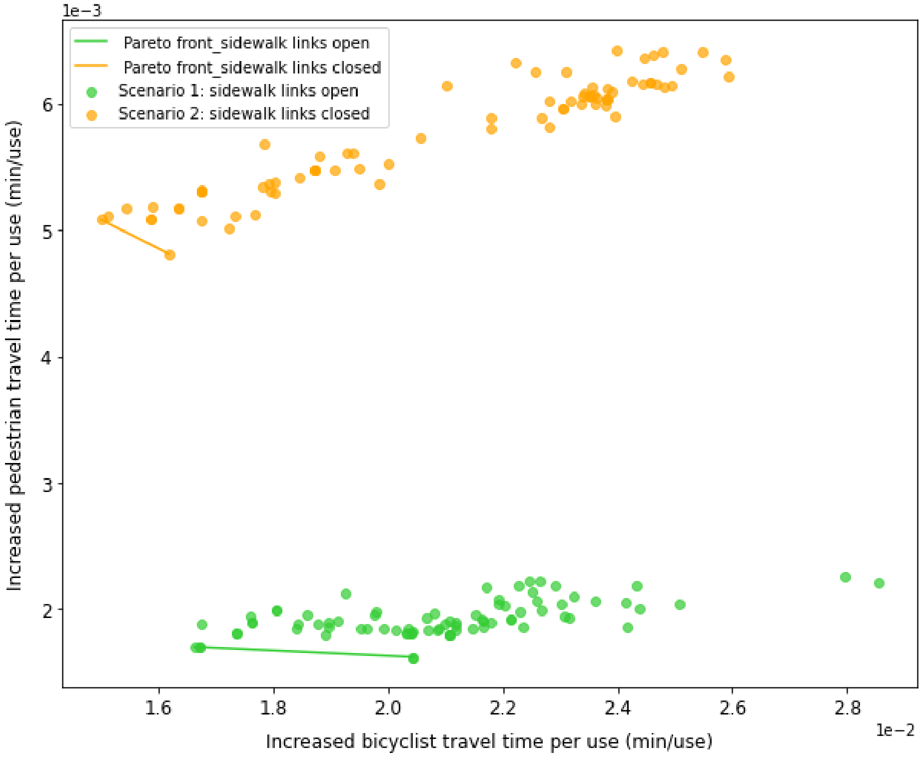

Figure 6-6 Increased Bicyclist Travel Time per Use versus Increased Pedestrian Travel Time per Use for Two Construction Scenarios

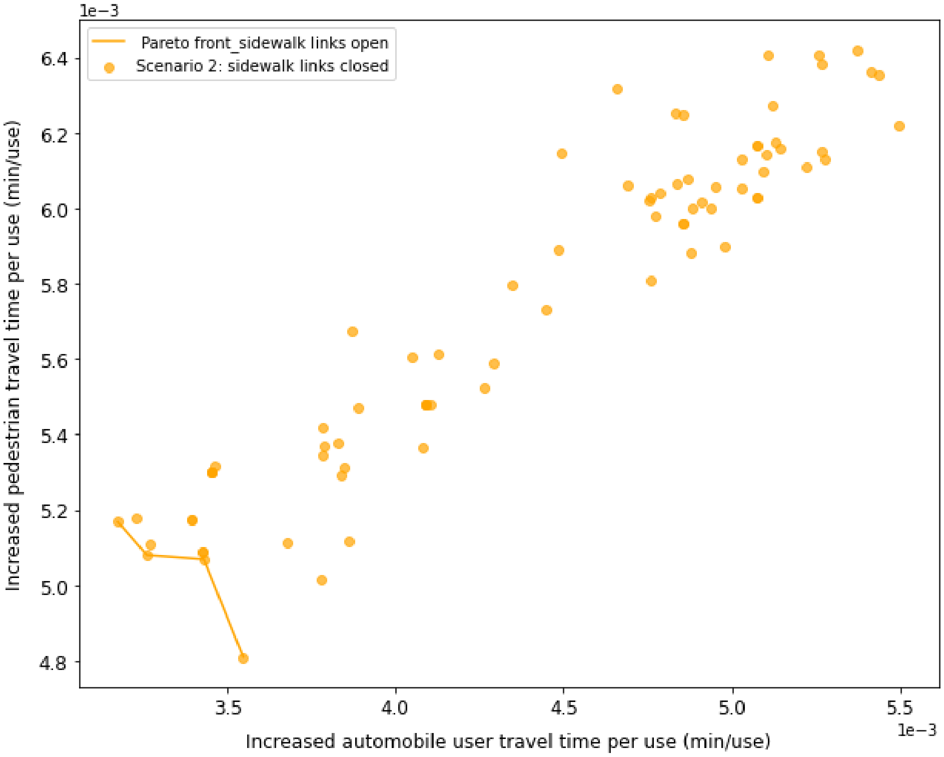

Figure 6-7 Increased Automobile User Travel Time per Use versus Increased Pedestrian Travel Time per Use for Construction Scenario 2

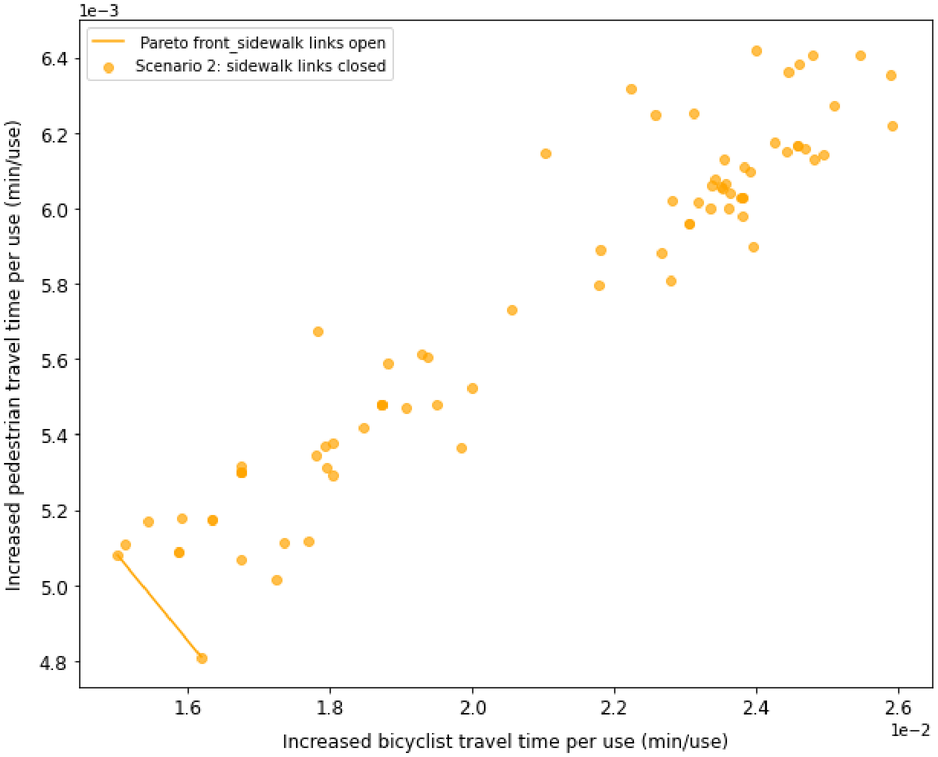

Figure 6-8 Increased Bicyclist Travel Time per Use versus Increased Pedestrian Travel Time per Use use for construction scenario 2.

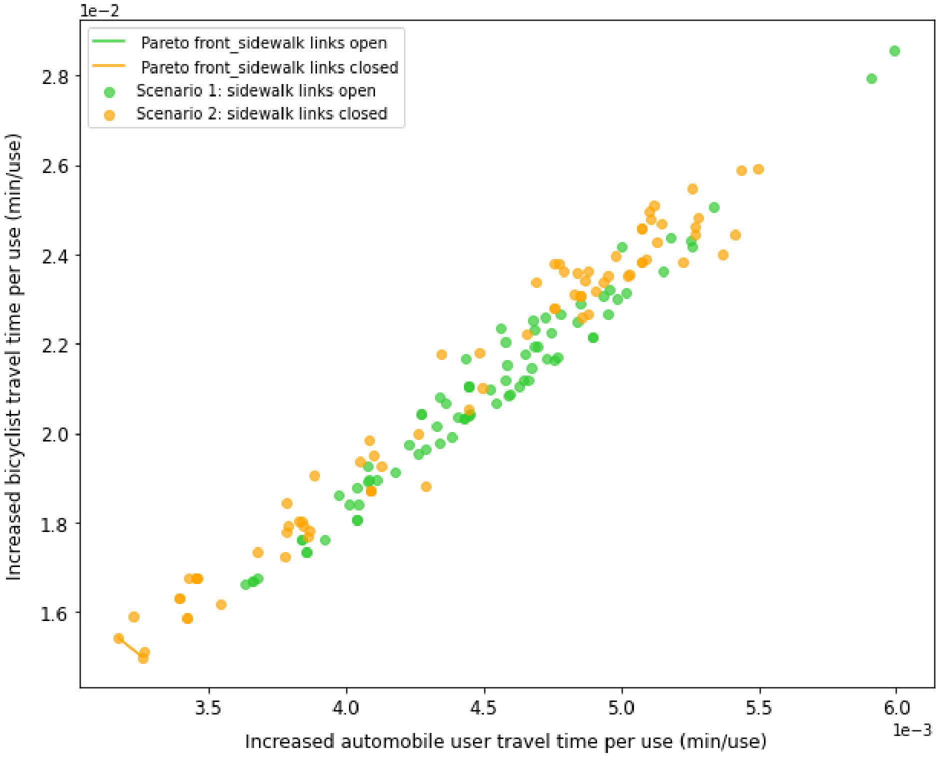

Figure 6-9 Increased Automobile User Travel Time per Use versus Increased Bicyclist Travel Time per Uuse for Two Construction Scenarios.

The Relationship and Trade-offs Between the Travel Times and the Total Agency Cost

The relationship between the travel time for the three modes and total agency cost is investigated using the competitors in the last generation from both construction scenarios. As expected, both the automobile travel time and bike travel time have a positive linear relationship with the total cost. This makes sense because the mode travel times can be reduced by reducing the number of mobilizations; in this study, the only way to reduce the number of mobilizations is to bundle projects from the same action category and same street. Doing that also reduces the mobilization cost and further reduces the total cost. This conclusion can be further observed in Figure 6-10 and Figure 6-11, where no clear Pareto fronts are observed. It means a reduction in total cost must lead to a reduction in automobile travel time and bicyclist travel time, and vice versa.

In Figure 6-12, scenario 2 has a much higher pedestrian travel time than scenario 1. The increased pedestrian travel time is caused by the closed links during reconstruction and major repair pavement projects. In scenario 1, the change in total cost does not influence the pedestrian travel time. This observation is close to the observation from Figure 6-3 and the reason is similar as well. For scenario 1, there are only 10 sidewalk projects that will affect the pedestrian travel time and the mobilization duration for these projects are relatively short. Therefore, the pedestrian travel time doesn’t change much with different bundling plans as well as total costs. Nevertheless, in scenario 2, the pedestrian travel time will be affected by 10 sidewalk projects and 24 pavement reconstruction and major repair projects. Therefore, in scenario 2, the pedestrian travel time and total cost are more correlated than in scenario 1. A more detailed look at the relationship between cumulative increased pedestrian travel time and total cost for construction scenario 2 can be seen in Figure 6-13. A clear positive correlation can be found between the two metrics in Figure 6-13.

In summary, in scenario 1, the total cost, cumulative increased automobile user travel time, and cumulative increased bicyclist travel time are positively correlated but not the cumulative increased pedestrian travel time. However, in scenario 2, all four mentioned metrics have a positive correlation. Therefore, selecting a bundling plan that has good performance in one metric would also yield good performance in the remaining three metrics.

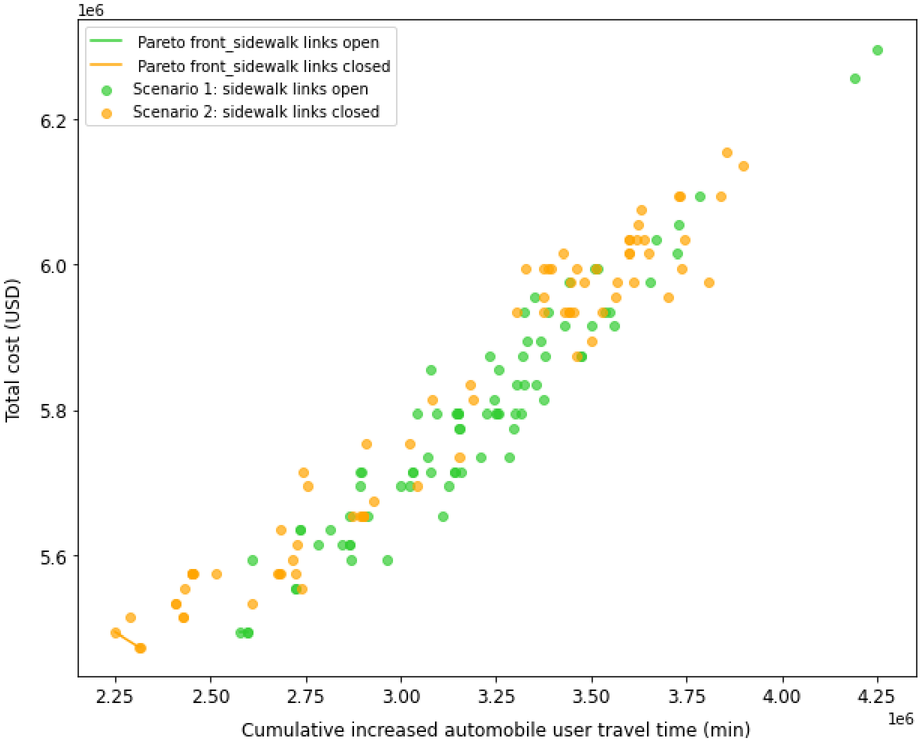

Figure 6-10 Cumulative Automobile User Travel Time versus Total Cost for the Two Construction Scenarios

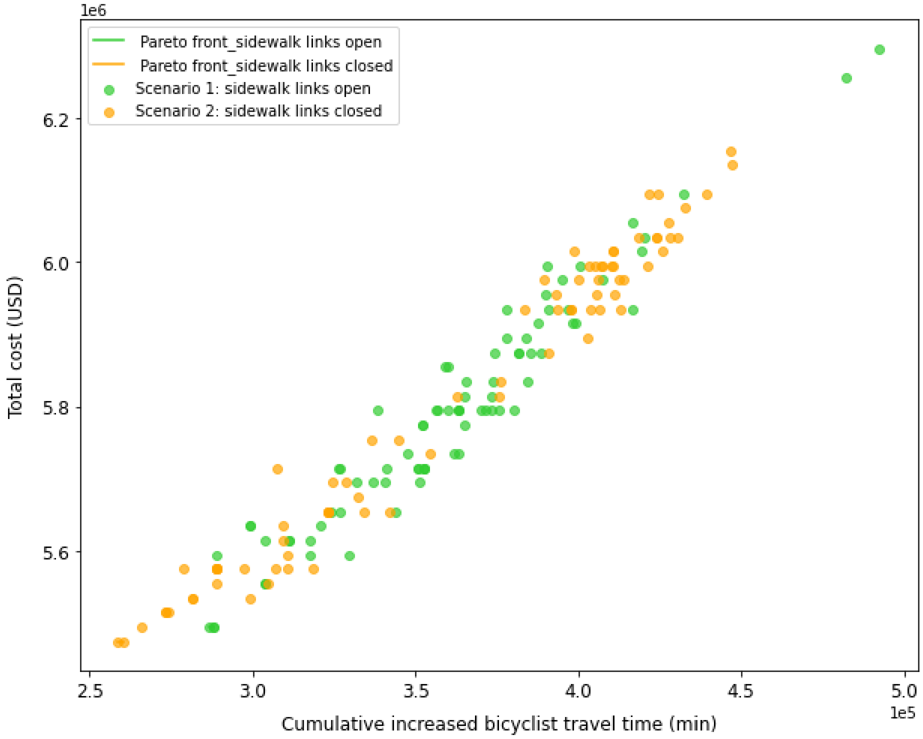

Figure 6-11 Cumulative Bicyclist User Travel Time versus Total Cost for the Two Construction Scenarios

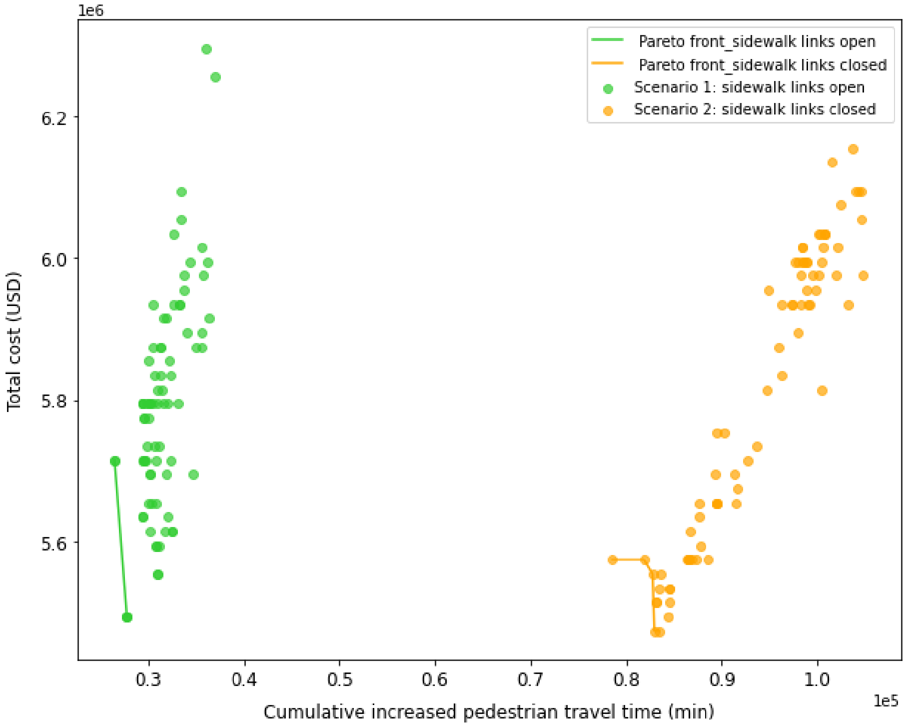

Figure 6-12 Cumulative Pedestrian User Travel Time versus Total Cost for the Two Construction Scenarios

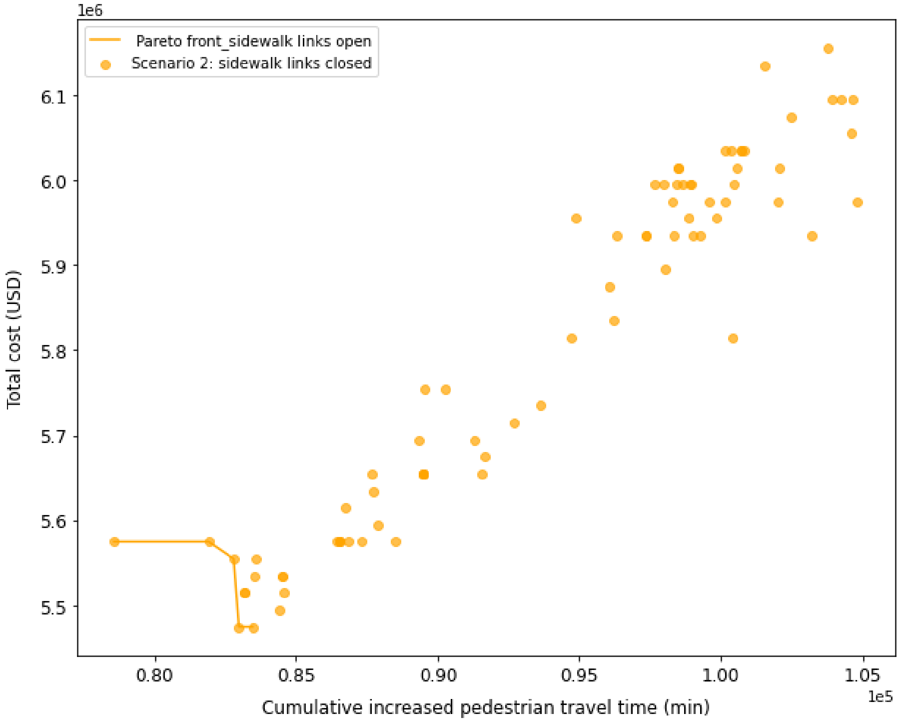

Figure 6-13 Cumulative Increased Pedestrian Travel Time versus Total Cost for Construction Scenario 2

The Relationship and Trade-offs Between the Standard Deviation of Travel Times and the Mean Annual Travel Times

Having too many projects of the same asset category in the same year can cause significant inconvenience to the corresponding mode users, especially ADA users. In this study, the standard deviation of annual increased travel times is used to measure the distribution evenness of impacts on annual increased travel times over the planning horizon. Minimizing the standard deviation of annual increased travel times can avoid having a huge adverse impact in a certain year.

The standard deviations of increased annual travel times and the mean annual increased travel times may not be dependent on each other. Minimizing the mean annual increased travel cost is the same as cumulative increased travel time. Bundling projects that belong to the same action category and on the same street in the same year will reduce both mean and cumulative travel times. To achieve small standard deviations, NSGA-II tends to evenly spread the projects from the same asset category (pavement, bikeway, and sidewalk) over the planning horizon. For example, consider a case where NSGA-II has evenly assigned the pavement/bikeway/sidewalk projects for 10 years and the standard deviations are thus reduced. Then, each year, there should be projects that still belong to the same asset category and action category. If those projects from the same action category are on the same street, then the number of mobilizations will be reduced as well as the mean travel time. However, if those projects from the same action category are on different streets, the mean travel time will be different. So, the increased annual travel times and the mean annual increased travel times are not necessarily correlated. The standard deviations of increased annual travel times are calculated using objective functions (6-6)-(6-8). The mean annual increased travel times are calculated using the following formula (6-2):

$$Mean\ annual\ increased\ travel\ time = \frac{Cumulative\ increased\ travel\ time\ in\ the\ planning\ horizon}{Number\ of\ years\ in\ the\ planning\ horizon} \quad (6\text{-}2)$$

The bundling plans in the last generation are extracted for analysis. The mean annual automobile travel time does not have a clear relationship as shown in Figure 6-14 and Figure 6-15. The Pareto fronts in Figure 6-14 show that in scenario 1, a 10^5 minute increase in mean annual increased automobile user travel time will result in a $1.5 * 10^4$ reduction in standard deviation, while the same amount of increase in automobile user travel time will result in a $7.5 * 10^4$ reduction in standard deviation in scenario 2. The Pareto fronts in Figure 6-15 show that, in scenario 1, if the mean annual increased bicyclist travel time is reduced from $3.75 * 10^4$ to $3.45 * 10^4$, the standard deviation will increase from $0.6 * 10^4$ to $1.45 * 10^4$. However, the increase in standard deviation is much less when we reduce the mean annual increased bicyclist travel time from $3.45 * 10^4$ to $2.8 * 10^4$ minutes. In scenario 2, the Pareto front is relatively linear. This indicates that the same amount of change in value will cause a proportional change in another value, and this holds no matter which bundling plan we are currently considering. In Figure 6-16, as can be expected, the mean annual increased pedestrian travel time increased significantly from scenario 1 to scenario 2. The Pareto front in scenario 1 indicates that a small change in mean annual increased pedestrian travel time will cause a large change in the standard deviation. It also shows that the mean annual increased pedestrian travel time and the standard deviation are not correlated. In Figure 6-17, it can be seen that the mean annual increased pedestrian travel time and the standard deviation of annual increased automobile travel time have a weak negative correlation. The Pareto front shows that the standard deviation decreases slightly when the mean annual increased pedestrian travel time increases from $0.78 * 10^4$ to $0.88 * 10^4$ minutes. After that, the standard deviation decreases significantly as the mean annual increased pedestrian travel time increases.

In summary, in scenario 1, the mean annual increased travel times don’t correlate with the corresponding standard deviations. The same observation is found in scenario 2 except for the pedestrians, where a weak negative correlation between the annual increased travel times and the standard deviation is found. This makes it difficult to select a good bundling plan when considering evenly distributing the impact on pedestrians, as it may increase the total costs and the travel times of all mode users.

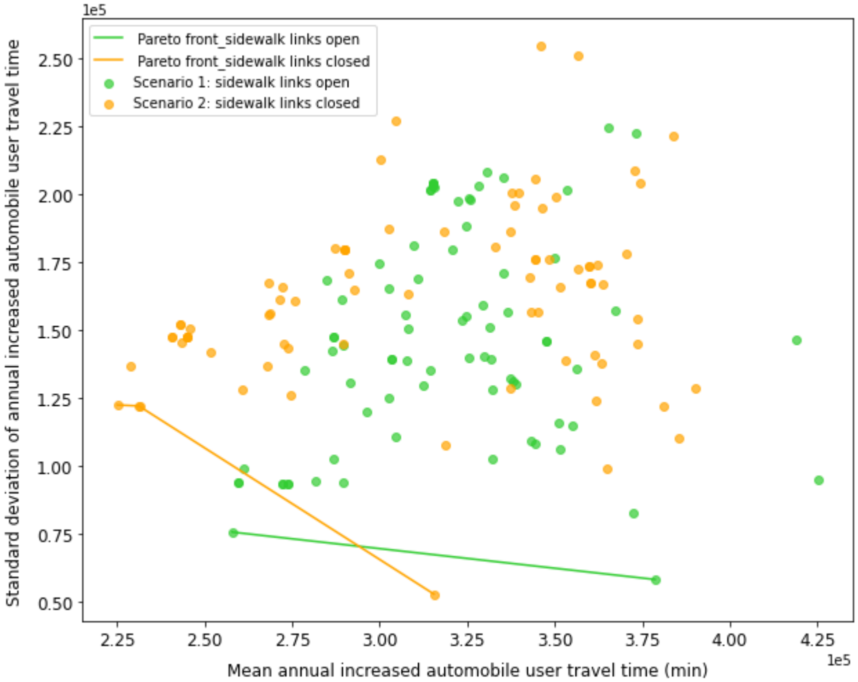

Figure 6-14 Mean Annual Increased Automobile User Travel Time versus Standard Deviation of Annual Increased Automobile User Travel Time for Two Construction Scenarios

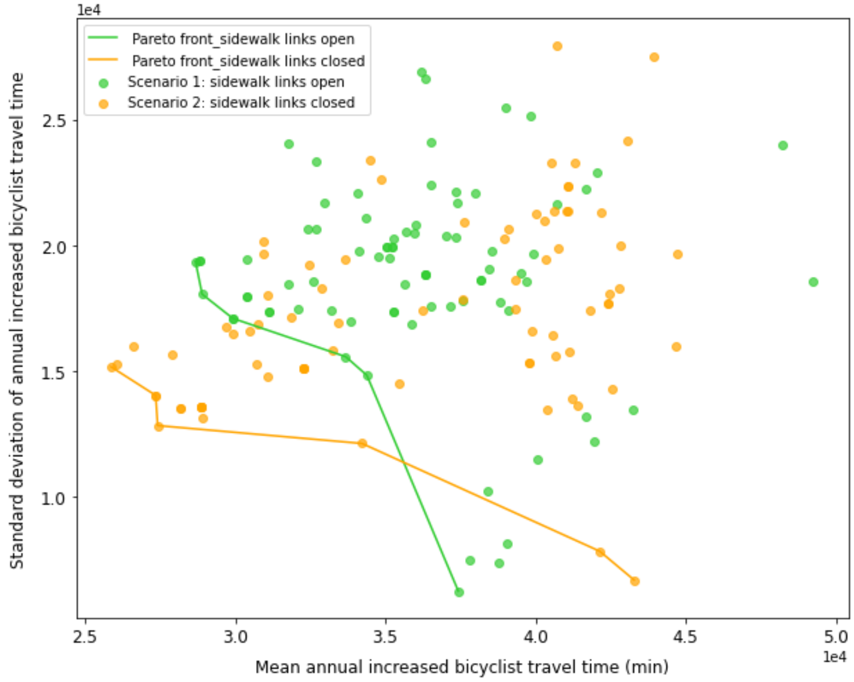

Figure 6-15 Mean Annual Increased Bicyclist Travel Time versus Standard Deviation of Annual Increased Bicyclist Travel Time for Two Construction Scenarios

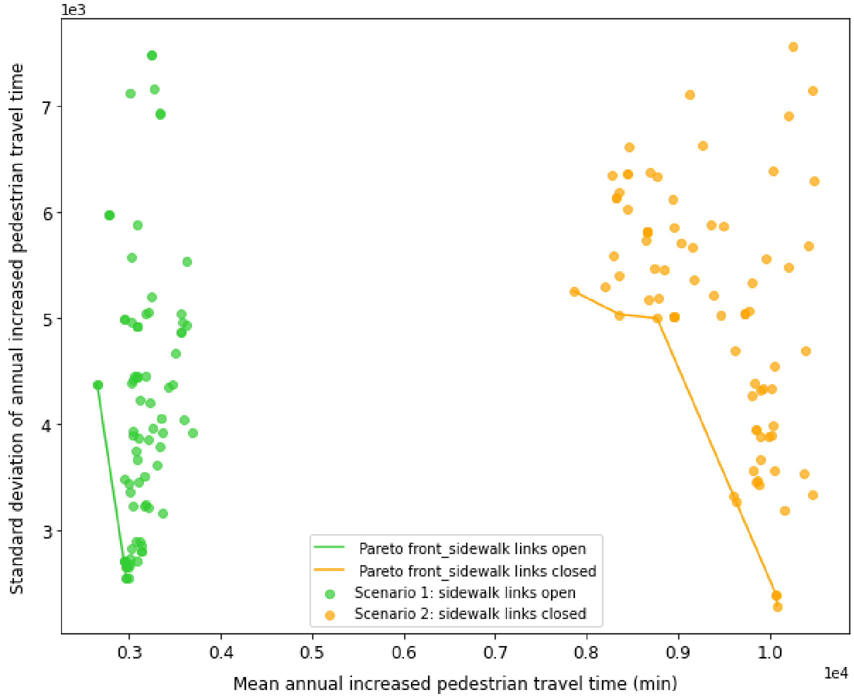

Figure 6-16

Mean Annual Increased Pedestrian Travel Time versus Standard Deviation of Annual Increased Pedestrian Travel Time for Two Construction Scenarios

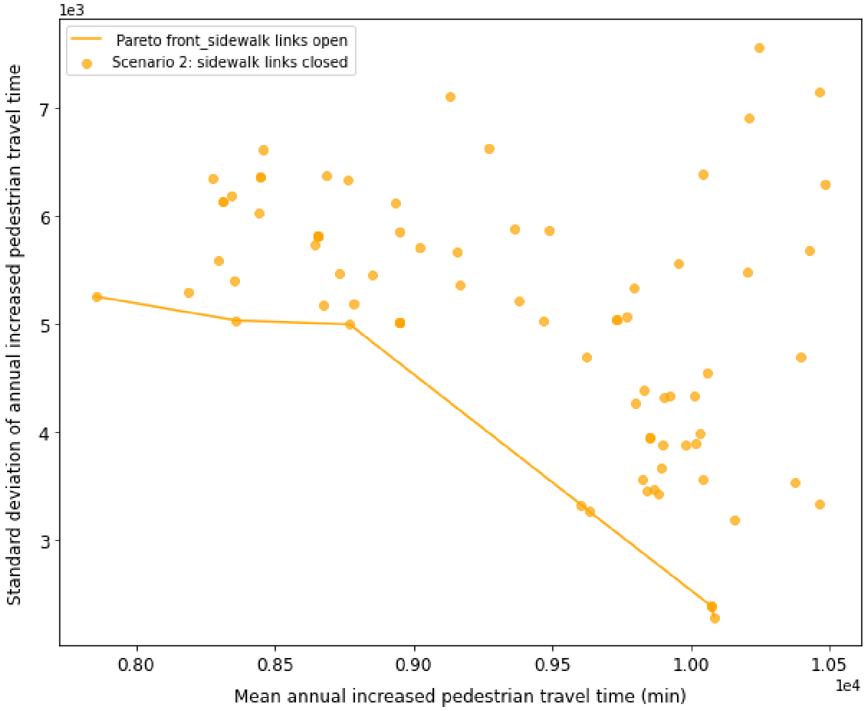

Figure 6-17 Mean Annual Increased Pedestrian Travel Time versus Standard Deviation of Annual Increased Pedestrian Travel Time for Two Construction Scenario 2

The Overall Performance of NSGA-II Project Bundling on the Study Network

The performance of NSGA-II for project bundling on the network is examined in terms of the total cost, cumulative increased automobile user travel time, cumulative increased bicyclist travel time, and cumulative increased pedestrian travel time. In each generation, the project bundling plan with the lowest cost is selected from 80 competitors to represent the best cost performance from that generation. As a result, 700 project bundling plans are selected along with their total costs.

To track the total cost change with algorithm iterations, the total costs are plotted against the generation steps as shown in Figure 6-18. As can be seen, the total cost decreases as NSGA-II gets into higher generations and tends to be stable after generation 500 for both scenarios. However, for scenario 1, the total cost converges a little slower at around generation 450 compared to scenario 1 converges at around generation 250. The converged total cost of scenario 1 is higher than that of scenario 2, being 5.49 and 5.47 million USD, respectively. One difference between the two scenarios in NSGA-II is that scenario 2 would have more tendency to put pavement projects on the same street in the same year to save mobilization cost, and therefore leads to a lower total cost. In other words, objective (6-4) in scenario 2 plays a more important role in minimizing total cost compared to scenario 1.

The cumulative increased travel times all stay stable after 600 generations as can be observed in Figure 6-19, Figure 6-20, and Figure 6-21. The cumulative increased automobile user and bicyclist travel times are higher in scenario 1 than in scenario 2. The reason is similar to that discussed above. In scenario 2, NSGA-II has more tendency to bundle pavement projects on the same street in the same year to also save mobilization duration. Therefore, this leads to lower cumulative increased automobile user and bicyclist travel times. Nevertheless, closing sidewalk links along with the pavement reconstruction and major repair projects has significantly increased the cumulative increased pedestrian travel time as shown in Figure 6-21.

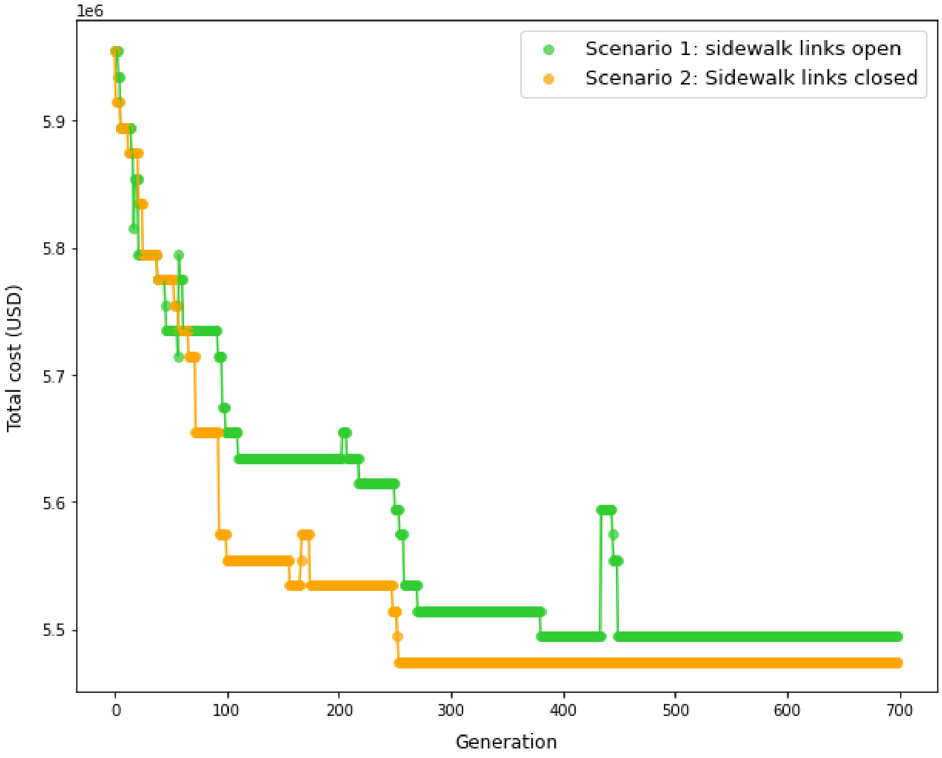

Figure 6-18 Total Cost versus Generation Steps for two Construction Scenarios.

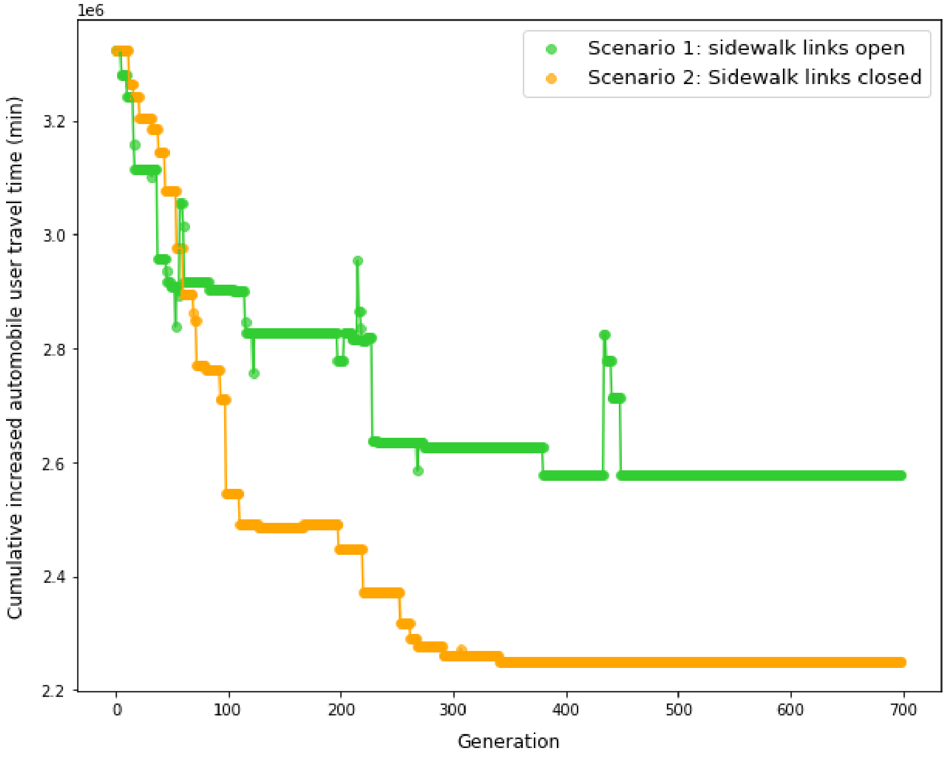

Figure 6-19 Cumulative Increased Automobile User Travel Time versus Generation Steps for Two Construction Scenarios

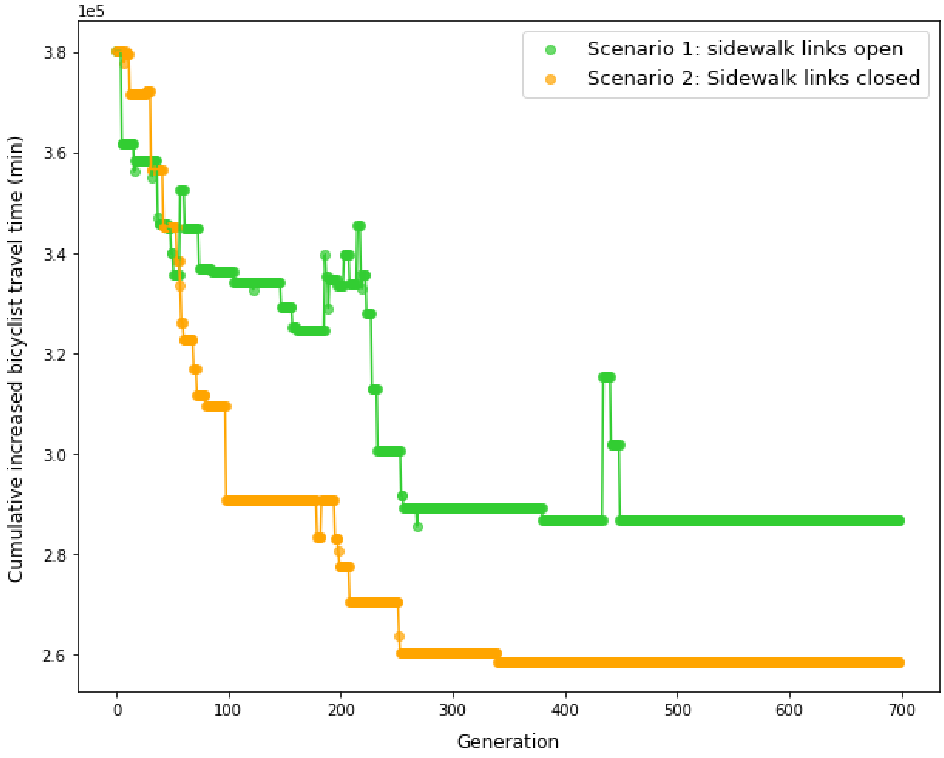

Figure 6-20 Cumulative Increased Bicyclist Travel Time versus Generation Steps for Two Construction Scenarios

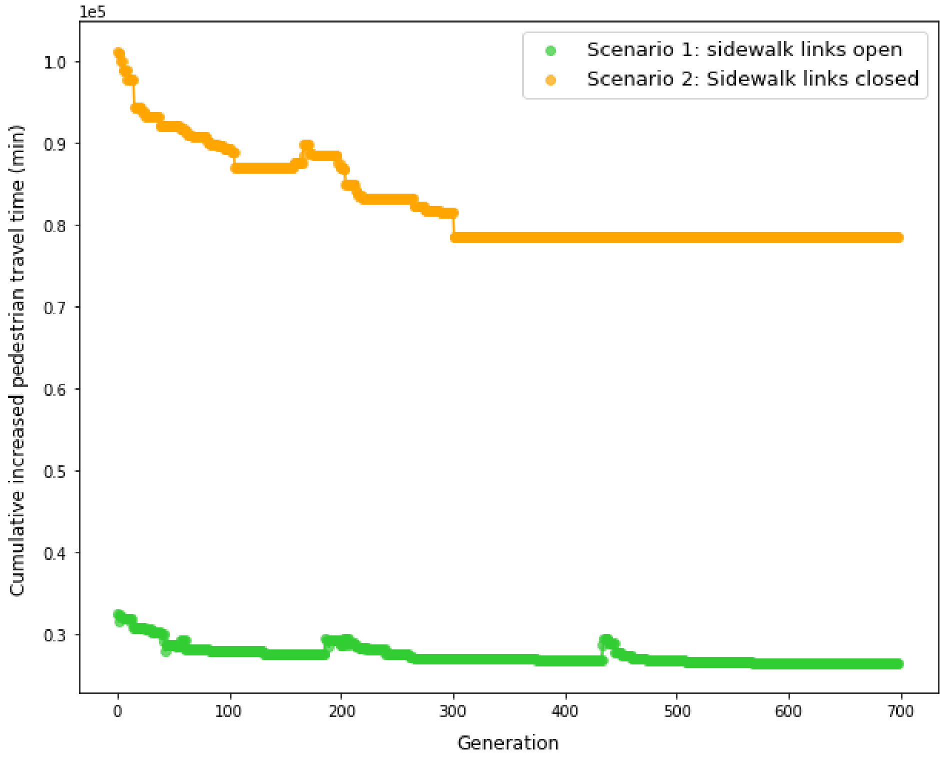

Figure 6-21 Cumulative Increased Pedestrian Travel Time versus Generation Steps for Two Construction Scenarios

LIMITATIONS

In this study, several assumptions are made to simplify the problem and reduce the computational time of NSGA-II. These assumptions enabled the consideration of additional objectives.

However, some assumptions are not in accordance with real world practices and should be addressed in future work. In this study, there is an annual construction budget limit for each year that is near the average annual budget. While a steady budget scenario can be advantageous in terms of labor force stability, this limits the NSGA-II from finding better bundling plans. A total budget over the entire 10-year planning horizon would be recommended, although maintaining a maximum on annual expenditures.

Projects were allowed to be scheduled at any time during the 10-year horizon without regard to continued condition deterioration. While incorporating deterioration models and related costs would be idea, a cap on years of deviation from the timing indicated by condition could be explored as a simplified approach. We also assume that the agencies only have access to one set of equipment for each action category, which means that no simultaneous projects from the same action category will happen. This may not be true for a larger transportation network and for work done by contractors. Being able to evaluate the impact of simultaneous projects could make this framework yield better bundling plans.

SUMMARY AND CONCLUSIONS

In this chapter, we aim to bundle pavement, bikeway, and sidewalk projects by year over a 10-year planning horizon and investigate the impacts of different bundling plans on total cost and travel times for three modes of users (automobiles, bicycles, pedestrians). The study area is located in the business district of Newark, Delaware. A total of 50 projects from five maintenance and rehabilitation action categories are considered. The project bundling problem is formulated as a MOMOKP. The objectives are defined as minimizing the total cost, minimizing cumulative increased travel times of users of the three modes, and minimizing the standard deviation of annual increased travel times of users of the three modes. Two construction scenarios are considered, the first scenario assumes the sidewalks remain open during roadway work while the second scenario assumes they are inaccessible during those intervals. The problem is solved using NSGA-II. The bundling plans in the last generation of NSGA-II are extracted for trade-off analysis.

It was found that in both scenarios, the total cost, cumulative increased travel times, cumulative increased travel times per use, and mean annual increased travel times are all positively correlated in both scenarios. In scenario 1, the standard deviation of annual increased travel times does not have a clear correlation with those metrics. Nevertheless, in scenario 2, the standard deviation of annual increased pedestrian travel times has a negative correlation with the metrics. This is important when policymakers don’t want to have a huge amount of impact on pedestrian travel time happen in one year, or when a specific population is being considered, such as ADA users. When the policymakers want to evenly distribute the travel time impact on pedestrians in the planning horizon, they may end up with higher agency costs and more travel times for all three mode users.

Closing sidewalk links may be more in accordance with real practices in many scenarios. However, the cumulative pedestrian travel time increases substantially from scenario 1 to scenario 2. This indicates pavement reconstruction and major repair projects would have a noteworthy negative impact on pedestrian travel time, highlighting another aspect of the known importance of preventive maintenance and minor repairs.

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CHAPTER 7

Evaluating Project Bundles

INTRODUCTION

Maintenance project plans are typically made with consideration for only a specific mode, such as roadways, railroads and waterways (Mahmoudzadeh et al., 2021). As personal vehicle trips account for 87% of daily trips in the US.(BTS, 2017), impacts of maintenance activities on automobile users is most often the focus.. However, in some areas, such as university campuses and central business districts (CBDs), where more non-motorized transportation facilities and higher volumes of pedestrians, bicycles and wheelchair users, impacts extend beyond automobile users. In practice, the impacts on non-motorized users are ignored in mainstream maintenance planning (Mirchandani and Peng, 2018).

Maintenance work may have a more significant impact on some special user groups, for example, older pedestrians and wheelchair users, than on the able-bodied non-motorized or motorized travelers. For example, when some segments of sidewalks are blocked for maintenance, wheelchair users may not be able to detour to the alternative sidewalk route as able-bodied pedestrian do, as they may have difficulty in climbing up lengthy or steep slopes, or traversing uneven surfaces, bumps or potholes along this alternative route. While the geographical characteristics of the alternative path induce little additional impacts on able-bodied pedestrians, this is not the case for mobility impaired users. Thus, in addition to the impact itself, the impacts from maintenance work on different user groups (especially the mobility impaired) should be evaluated. Studies thatconsider impacts on special groups are quite limited, and most related works are only practice oriented (Harrison, 2007); they focus on improving accessibility for the mobility impaired users only under non-maintenance conditions through special facility designs.

Additionally, user preferences for routes may change as a consequence of maintenance work. To model user mode and route choice in multi-modal networks, a utility function that models user travel costs as a function of flows on the arcs along candidate routes is often used (Patriksson, 1994). However, in multi-modal transportation networks in university campuses, or CBDs, or low-income countries, where non-motorized travelers often share lanes with motorized vehicles, users who must detour to a unfamiliar path due to disruptions from maintenance on their facilities or other co-located facilities will likely give more weight to factors that might not ordinarily be of great influence.. For example, safety may have a much higher weight in choosing a route than in normally operating environments. Thus, these models need to account for additional attributes that pertain to special needs of each user type in applying these methods in these special circumstances.

To provide a comprehensive evaluation of impact of maintenance decisions on different user groups, this study incorporated factors related to travel cost, accessibility, and safety for each user group into the multi-modal network modeling. An embedded traffic assignment model in mixed traffic of different modes is solved through a fast bush-based traffic assignment algorithm (Dial, 2006). Measurements of mobility, accessibility, safety, and relative changes of impacts among different user groups are considered in impact evaluation under varying demand scenarios. While not completed in this analysis, system-wide proportional fairness (Kelly et al., 1998) could also be considered.

The developed method and metrics were applied to the case study presented in Chapter 4 representing a portion of the business district of Newark, Delaware, which is adjacent to the campus of the University of Delaware.

Chapter 6 explored strategies for bundling the fifty projects identified for the study area listed in Appendix D to develop a construction schedule for a ten-year planning horizon. A multi-objective multidimensional knapsack problem (MOMKP) is solved using a non-dominated sorting genetic algorithm II (NSGA-II) for each of seven different objective functions, where travel times are based on a shortest path algorithm. Using a maximum annual construction budget of 0.55 million USD, each bundle (or knapsack) contains a list of project indices indicating which project should be implemented in which year.

The analysis in Chapter 6 was based on the following seven objective functions:

- Objective Function 1) Minimize agency cost (total construction and mobilization cost)
- Objective Function 2) Minimize cumulative increased automobile user travel time
- Objective Function 3) Minimize cumulative increased pedestrian user travel time
- Objective Function 4) Minimize cumulative increased bicyclist user travel time
- Objective Function 5) Minimize the standard deviation of annual increased automobile user travel time (impact to automobile user is spread evenly into 10 years)
- Objective Function 6) Minimize the standard deviation of annual increased pedestrian user travel time (impact to pedestrian user is spread evenly into 10 years)
- Objective Function 7) Minimize the standard deviation of annual increased bicycle user travel time (impact to bicycle user is spread evenly into 10 years)

Further consideration of the objectives used in Chapter 6 suggested that decision makers are likely to find it difficult to understand the concept of minimizing the standard deviation of travel time, and decision makers are also interested in objectives that minimize total costs, such as the weighted total travel time increase and agency costs. Seven perspectives were identified as follows, the first four of which are identical to objectives 1 to 4. Furthermore, comparing the results to a random selection of projects provides a benchmark.

- Perspective 1) Minimal agency cost (total construction and mobilization cost)
- Perspective 2) Minimal cumulative increased automobile user travel time
- Perspective 3) Minimal cumulative increased pedestrian user travel time
- Perspective 4) Minimal cumulative increased bicyclist user travel time
- Perspective 5) Minimal cumulative agency cost and increased user travel time, assuming all components are equally weighted and travel times are converted to monetary units assuming 20USD/hour
- Perspective 6) Minimal cumulative increased user travel time, assuming all components are equally weighted and travel times are converted to monetary units assuming $20US/hour
- Perspective 7) Random selection of projects.

The following section describes the bundles for the seven objectives identified in Chapter 6 and the seven perspectives used in this chapter. The subsequent section evaluates the project bundles only for the seven perspectives on the case study location. A concluding section discusses the results.

PROJECT BUNDLES

The project bundles for each **objective function** from Chapter 6 are shown in Table 7-1. For each objective function and for each year, the entries represent the projects to be undertaken in that year. For example, for Objective Function 1 (minimize agency costs), [7, 30, 31] indicates that Projects 7, 30, and 31 (see **Error! Reference source not found.** for project descriptions) are completed in Year 2. It is notable that many projects have similar schedules for Objective Functions 1, 2, 3 and 4, but the bundling (and scheduling) changes significantly when the standard deviations of travel times are considered.

The project bundles for each **perspective** are shown in. Table 7-2. Table 7-2 shows that several projects are scheduled in the same year under different perspectives. In fact the project bundles for Scenarios 1, 2, 3 and 4 are the same for years 1, 3, 4 and 5. To understand these similarities, a bubble chart, shown in Figure 7-1, was developed. The size of the bubble reflects the number of perspectives in which this project appears in the same year, indicating similarities in priorities. Each bubble is labeled with the perspectives in which the project occurs (the perspectives are in parentheses) and the Project ID. For example, Project 31 is scheduled for Year 3 in Scenarios 1, 2, 3 and 4. The label shows "(1,2,3,4), 31". Both Table 7-2 and Figure 7-1, show that there are many similarities among Perspectives 1, 2, 3 and 4 and among Perspectives 5, 6 and 7.

Table 7-1 Project Bundles for the Seven Objective Functions

Year	Objective Function 1: Minimum Agency Cost	Objective Function 2: Minimum Increased Automobile User Travel Time
1	[6, 28, 29]	[6, 28, 29]
2	[8]	[37]
3	[7, 30, 31]	[7, 30, 31]
4	[18, 19, 21, 22]	[18, 19, 21, 22]
5	[2, 3, 4, 5]	[2, 3, 4, 5]
6	[17, 20, 23, 24, 25, 26, 27, 32, 33]	[17, 20, 23, 24, 25, 26, 27, 32, 33]
7	[36, 37, 40, 41]	[0, 1, 36, 40, 47]
8	[0, 1, 9, 39]	[8, 9, 34, 41, 42, 43]
9	[11, 14, 15, 16, 38, 42, 43, 46]	[10, 11, 12, 13, 14]
10	[10, 12, 13, 34, 35, 44, 45, 47, 48, 49]	[15, 16, 35, 38, 39, 44, 45, 46, 48, 49]
	Objective Function 3: Minimum Increased Pedestrian User Travel Time	Objective Function 4: Minimum Increased Bicycle User Travel Time
1	[6, 28, 29]	[6, 28, 29]
2	[27]	[37]
3	[7, 30, 31]	[7, 30, 31]
4	[18, 19, 21, 22]	[18, 19, 21, 22]
5	[2, 3, 4, 5]	[2, 3, 4, 5]
6	[8, 17, 20, 23, 24, 25, 26]	[17, 20, 23, 24, 25, 26, 27, 32, 33]
7	[1, 32, 33, 36, 40, 47]	[0, 1, 36, 40, 47]
8	[0, 9, 34, 37, 41]	[8, 9, 34, 41, 42, 43]
9	[10, 11, 12, 13, 14, 42, 43]	[10, 11, 12, 13, 14]
10	[15, 16, 35, 38, 39, 44, 45, 46, 48, 49]	[15, 16, 35, 38, 39, 44, 45, 46, 48, 49]
	Objective Function 5: Minimize the Standard Deviation of Automobile User Travel Time	Objective Function 6: Minimize the Standard Deviation of Pedestrian User Travel Time
1	[6, 28, 29]	[6, 28, 29]
2	[27]	[3, 12, 18, 23, 25, 31, 45]
3	[7, 30, 31]	[4, 22, 26, 37, 39]
4	[18, 19, 21, 22]	[17, 20, 27, 32, 33, 34, 35, 42, 47]
5	[2, 3, 4, 5]	[1, 13, 19, 38, 40]
6	[8, 17, 20, 23, 24, 25, 26]	[0, 8, 9, 14]
7	[1, 32, 33, 36, 40, 47]	[11, 15, 24, 41, 43, 46]
8	[0, 9, 34, 37, 41]	[2, 16, 21]
9	[10, 11, 12, 13, 14, 42, 43]	[7, 48, 49]
10	[15, 16, 35, 38, 39, 44, 45, 46, 48, 49]	[5, 10, 30, 36, 44]
	Objective Function 7: Minimize the Standard Deviation of Bicycle User Travel Time	
1	[10, 11, 27, 31, 41]	
2	[6, 46]	
3	[4, 13, 14, 15]	
4	[0, 8, 20, 35, 38, 42, 43, 48, 49]	
5	[2, 5, 19, 37, 40, 45]	
6	[1, 3, 21, 34, 36, 44, 47]	
7	[12, 33]	
8	[7, 29, 30]	
9	[9, 16, 17, 24, 26, 32]	
10	[18, 22, 23, 25, 28, 39]	

Table 7-2 Project Bundles for the Seven Perspectives

Year	Perspective 1: Based on Minimum Agency Cost	Perspective 2: Minimum Increased Auto User Travel Time
1	[6, 28, 29]	[6, 28, 29]
2	[8]	[37]
3	[7, 30, 31]	[7, 30, 31]
4	[18, 19, 21, 22]	[18, 19, 21, 22]
5	[2, 3, 4, 5]	[2, 3, 4, 5]
6	[17, 20, 23, 24, 25, 26, 27, 32, 33]	[17, 20, 23, 24, 25, 26, 27, 32, 33]
7	[36, 37, 40, 41]	[0, 1, 36, 40, 47]
8	[0, 1, 9, 39]	[8, 9, 34, 41, 42, 43]
9	[11, 14, 15, 16, 38, 42, 43, 46]	[10, 11, 12, 13, 14]
10	[10, 12, 13, 34, 35, 44, 45, 47, 48, 49]	[15, 16, 35, 38, 39, 44, 45, 46, 48, 49]
	Perspective 3: Minimum Increased Pedestrian User Travel Time	Perspective 4: Minimum Increased Bicycle User Travel Time
1	[6, 28, 29]	[6, 28, 29]
2	[27]	[37]
3	[7, 30, 31]	[7, 30, 31]
4	[18, 19, 21, 22]	[18, 19, 21, 22]
5	[2, 3, 4, 5]	[2, 3, 4, 5]
6	[8, 17, 20, 23, 24, 25, 26]	[17, 20, 23, 24, 25, 26, 27, 32, 33]
7	[1, 32, 33, 36, 40, 47]	[0, 1, 36, 40, 47]
8	[0, 9, 34, 37, 41]	[8, 9, 34, 41, 42, 43]
9	[10, 11, 12, 13, 14, 42, 43]	[10, 11, 12, 13, 14]
10	[15, 16, 35, 38, 39, 44, 45, 46, 48, 49]	[15, 16, 35, 38, 39, 44, 45, 46, 48, 49]
	Perspective 5: Minimum Total Costs	Perspective 6: Minimum Total Travel Time
1	[11, 12, 13, 14, 15, 16]	[11, 12, 13, 14, 15, 16]
2	[18, 37, 40, 41]	[18, 37, 40, 41]
3	[19, 22, 24, 25, 26, 27, 46, 47]	[19, 22, 24, 25, 26, 27, 46, 47]
4	[2, 3, 10, 34, 35, 44, 45, 48, 49]	[2, 3, 10, 34, 35, 44, 45, 48, 49]
5	[8, 9, 32, 33, 36, 38]	[8, 9, 32, 33, 36, 38]
6	[0, 1, 21, 30, 31, 42, 43]	[0, 1, 21, 30, 31, 42, 43]
7	[39]	[39]
8	[6]	[6]
9	[7]	[7]
10	[4, 5, 17, 20, 23, 28, 29]	[4, 5, 17, 20, 23, 28, 29]
	Perspective 7: Random Selection	
1	[0, 19, 30, 35, 36, 38, 39, 43, 44]	
2	[1, 10, 15, 17]	
3	[2, 8, 12, 18, 28, 31, 33, 41]	
4	[4, 20, 23, 37, 42, 46]	
5	[6, 24, 26]	
6	[3, 13, 14, 16, 21, 47, 49]	
7	[5, 34, 40]	
8	[7, 27, 32]	
9	[9, 11, 22, 25, 29, 45, 48]	
10	[0, 19, 30, 35, 36, 38, 39, 43, 44]	

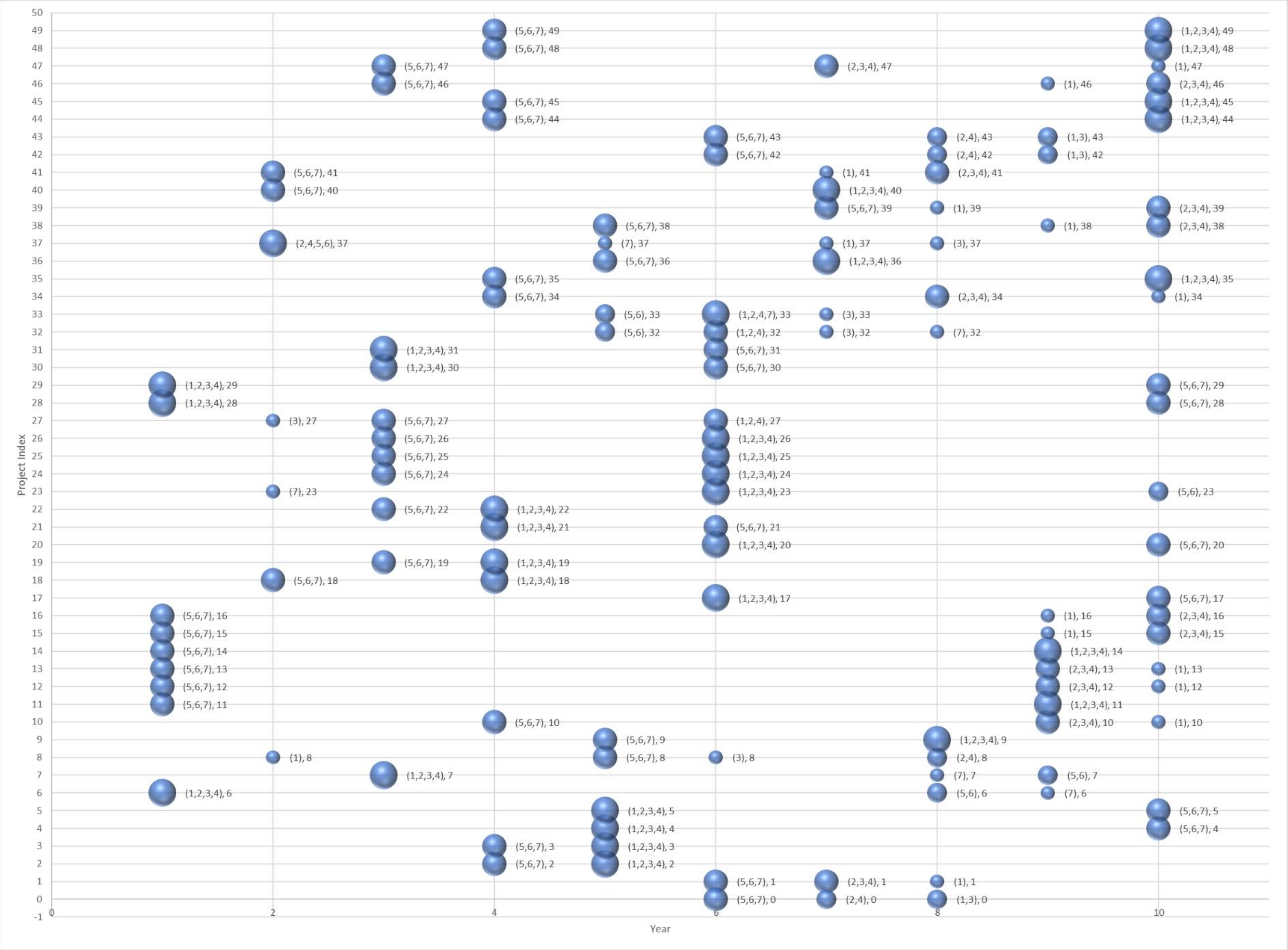

Figure 7-1 Projects Assigned to Years (Labels Indicate the Perspectives and Project Index)

EVALUATION

Evaluation of the project bundles is based on the seven perspectives. These perspectives are each evaluated in terms of average travel times for each mode and average travel time for all users, as well as the number of infeasible trips. Other performance metrics, such as sustainability, described in Chapter 4, might also be evaluated, but this is beyond the scope of this project and would require a larger case study area.This project focused on efficiency, accessibility and mobility (via walkabililty and bikeability), equity and safety, the key concerns identified in Chapter 4.

Alternative demand scenarios are then explored for each of the perspectives to understand how changes in demand and the different strategies (perspectives) to select projects influences the performance in terms of travel time and trip feasibility. The evaluation is based on traffic flow patterns on the multi-modal network, following a traffic assignment procedure that loads the demands of different modes onto the network. Interactions between automobile and bike traffic flows are modeled in the assignment, while pedestrian demands (including those of mobiliy impaired users) are assumed to use an exclusive sidewalk network without experiencing congestion effects.

Seven Perspectives

The evaluation of the project bundles focused on the seven perpectives, travel time and the number of infeasible trips. Table 7-3 shows the average travel time and the number of infeasible trips for the base case (no link closures) and for each scenario. The combined average travel time (Com. Avg. in Table 1-3) is the travel time for each mode weighted by the demand for each mode. It is worth noting that the minimum combined average travel time in Table 7-3 occurs for the Minimal Auto Time perpective, not the Minimal Total Time perspective. This is likely because the project bundle was developed using a shortest path algorithm rather than user equilibrium traffic assignment.

In all scenarios, travel times increase for all modes as links are closed for maintenance and improvement. For example, the average travel time for automobiles increased from 2.96 minutes per trip in the base case to a minimum of 5.09 minutes per trip obtained in the perspective based on minimal total automobile travel time. The average travel time for cyclists increased from 17.74 minutes per trip in the base case to a minimum of 18.09 minutes under the perspective based on minimal total bike travel time.

The perspective based on minimal automobile total travel time has the combined minimum average travel time of all uses (5.85 minutes) and the Pareto least average travel time of all modes (5.09 minutes for automobile, 18.09 for bike and 25.23 for pedestrian (nearly as good as the optimal 25.22 minutes)) among the 7 maintenance perspectives. Automobile travel demand accounts for over 95% of total demand. It is plausible that optimization of the maintenance plan to minimize the total travel time of automobiles during maintenance will also lead to the combined minimum average travel time of all modes. This is expected, because the number of pedestrians and cyclists under existing demand conditions is very small in comparison to the number of automobiles.

Furthermore, some auto trips are infeasible in the network model as shown in Table 1-3. In practice these trips are feasible, but will have a very large increase in travel time as users navigate outside the network modeled. All bicycle and pedestrian trips are feasible as there are alternate paths under all considered maintainance bundles.

Table 7-4 provides results from maintenance scenarios with existing demand considering changes in safety risk for non-automobile users. The risk score here is calculated based on the raw risk score calculated to rank safety level of non-automobile links in a multi-modal network (Monsere et al., 2017). In this study, a link is assigned a score of one if its raw risk score ranked in the first 50 percentile (defined by a raw risk score of 43 and 34 for the pedestiran arcs and bike arcs, repectively) among all non-motorized links. It is assigned a score of zero, otherwise. The raw risk scores for this network were determined by many factors related to roadway configuration and corresponding traffic volumes. The scores for each link with and without construction are included in Appendix E (Table E-1 and Table E-2). Detailed calculation methods for the raw risk score can be found in (Monsere et al., 2017).

The results in Table 1-4 indicate a small risk increase for bike users as a consequence of construction is incurred due to the blocking of a bike lane due to maintenance. As a result, cyclists must reroute to links of higher risk score. The risk score for pedestrians remains unchanged.

Table 7-3 Impact metrics in peak hour in all perspectives (existing demand)

	Avg. travel time (minutes)				**Number of infeasible trips**		
Perspective	Auto.	Bike	Ped	Com. Avg.	Auto.	Bike	Ped
Base case	2.96	17.74	25.04	3.81	0	0	0
1: Min. Agency Cost	5.26	18.09	25.23	6.01	79	0	0
2: Min. Auto Time	5.09	18.09	25.23	5.85	63	0	0
3: Min. Ped Time	5.20	18.20	25.22	5.96	78	0	0
4: Min. Bike Time	5.09	18.09	25.23	5.85	63	0	0
5: Min. Total Cost	5.50	18.09	25.26	6.25	58	0	0
6: Min. Total Time	5.50	18.09	25.26	6.25	58	0	0
7: Randomly Selected	5.73	18.09	25.25	6.46	57	0	0

Table 7-4 Average values of risk scores for non-automobile users in peak hour in all perspectives (existing demand)

	Risk score	
Perspective	Bike	Ped.
Base case (no block)	1.24	8.00
1: Min. Agency Cost	1.27	8.01
2: Min. Auto Time	1.27	8.01
3: Min. Ped. Time	1.28	8.01
4: Min. Bike. Time	1.27	8.01
5: Min. Total Cost	1.28	8.00
6: Min. Total Time	1.28	8.00
7: Randomly Selected	1.27	8.01

Table 7-5 shows that the relative changes in average travel time, number of infeasible trips, and risk score due to the execution of a maintenance bundle derived under each perspective. The changes due to maintenance are not equally distributed across the modes. Relative changes in average travel time are calculated as the percentage increase in average travel time compared to the base case for the given demand and corresponding mode. The same method is used to calculate the relative changes in the average risk score. Relative changes in number of infeasible trips are calculated as the percentage of infeasible trips compared to the maintenance perspective for the given demand and corresponding mode. Automobile users take the largest impact on travel time with an average travel time increase by between 72% and 94% , inferring that this mode is more severely impacted than is the bike or pedestrian modes with relative changes in travel time at less than 3%. With trivial relative changes in all three measurements, the pedestrian is least impacted. The relative changes in number of infeasible trips are trivial for all three modes. The bike mode is the only mode impacted in terms of risk.

Table 7-5 Relative changes of impacts in peak hour in all maintenance perspectives (existing demand)

	Change in avg. travel time			**Change in number of infeasible trips**			**Change in avg. Risk score**	
Perspective	Auto.	Bike	Ped.	Auto.	Bike	Ped.	Bike	Ped.
1: Min. Agency Cost	78%	2%	1%	1%	0	0	3%	0
2: Min. Auto Time	72%	2%	1%	0	0	0	3%	0
3: Min. Ped. Time	76%	3%	1%	0	0	0	3%	0
4: Min. Bike. Time	72%	2%	1%	0	0	0	3%	0
5: Min. Total Cost	86%	2%	1%	0	0	0	3%	0
6: Min. Total Time	86%	2%	1%	0	0	0	3%	0
7: Randomly Selected	94%	2%	1%	0	0	0	3%	0

A link with a grade steeper than 2% was assumed to be inaccessible for mobility impaired pedestrians. Additional computations indicate that the 13% of pedestrians who are mobility-impaired would incur significant travel time increases. By comparison, if all pedestrians were assumed to be able-bodied, the average pedestrian travel time would be reduced to approximate 17 minutes for a 30% decrease under all maintenance perspectives. While the results for all perspectives are similar, they are not identical. This is not surprising as only one segment is inaccessible to mobility impaired users.

This result implies that mobility-impaired pedestrians suffer much longer travel time than the able-bodied pedestrians given the maintenance plans introduced under all of the perspectives. It is also worth noting that the average risk score is also slightly reduced from 8.0 to 7.9, after all pedestrians are assumed to be able-bodied .

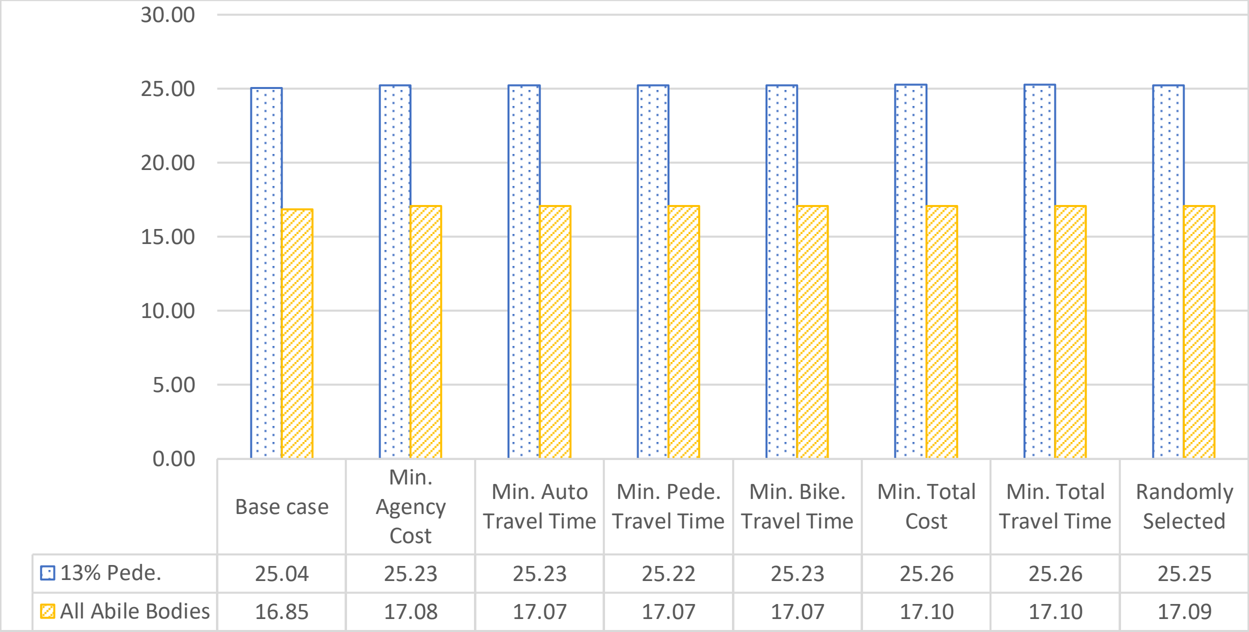

Figure 7-2 Average pedestrian travel time for perspectives using the existing O-D demand under an assumption that all users are able-bodied

Alternative Demand Scenarios

This analysis of travel time and number of infeasible trips was repeated for four additional demand scenarios as described in Table 7-6. Demand Scenario 0 is the base case, reflecting current peak hour weekday demand. Demand Scenarios 1 and 2 reflect significant growth in non-motorized demand (a doubling and fivefold increase). Demand Scenario 3 reflects a shift of 50% of automobile demand to non-motorized modes. Demand Scenario 4 incurs a doubling of all demand types. The following subsections present the results for the four demand scenarios.

Table 7-6 Scenarios for Variation in Trip Demand

No.	Demand variation method	Scenario background
0	None	Current peak hour in typical weekdays
1	Double both bike and pedestrian demand	Nonmotorized demand increase mildly during weekends
2	Five times both bike and pedestrian demand	Nonmotorized demand increase dramatically during a big celebrating event day
3	50% of current automobile demand shifts to nonmotorized demand	Current motorized demand shifts to nonmotorized in a “green travel future”
4	Double all demand	Demand of all modes increases because of community population growth

What if nonmotorized travel demand increases (Demand Scenarios 1 and 2)?

In demand scenarios in which nonmotorized demand is doubled (Table 7-7), average travel times and risk scores increase slightly for all modes for all perspectives, while the average number of infeasible trips for automobiles is unchanged. For all eight perspectives, the average travel time for automobile increased between 3 and 5%, while the average travel time increase for bikes is between 1 and 2%. The risk scores for pedestrians remain the same while risk scores for bikes increases marginally.

In demand scenarios in which nonmotorized demand is five times that of the existing demand (Table 7-8), average travel times increase more dramatically. For automobiles and bikes, the average travel time increase between 16 and 24% and 6% and 8%, respectively. The risk scores for pedestrians remain unchanged in comparison to scores under the base case demand while the risk scores for bikes increase by approximately 9%.

The increased bike flow on sharrow-bike lanes reduced the speeds for automobiles on the lanes. In the two demand scenarios, the average travel time and number of infeasible trips for pedestrians remained unchanged. This is because no congestion effects were assumed in pedestrian traffic assignment, and the sidewalk network is highly connected so accessibility is not affected by any maintenance actions.

Table 7-7 Average Values of Impact Metrics in Peak Hour with Doubled Nonmotorized Demand

	Avg. travel time (minutes)				**Number infeasible trips**			**Risk Score**	
Perspectives	Auto.	Bike	Ped	Com. Avg.	Auto.	Bike	Ped	Bike	Ped
Base case (no block)	3.11	17.98	25.04	4.72	0	0	0	1.28	8.00
1: Min. Agency Cost	5.46	18.38	25.23	6.89	79	0	0	1.28	8.01
2: Min. Auto Time	5.29	18.39	25.23	6.74	63	0	0	1.28	8.01
3: Min. Ped. Time	5.42	18.51	25.22	6.86	78	0	0	1.28	8.01
4: Min. Bike. Time	5.29	18.39	25.23	6.74	63	0	0	1.28	8.01
5: Min. Total Cost	5.70	18.38	25.26	7.11	58	0	0	1.28	8.00
6: Min. Total Time	5.70	18.38	25.26	7.11	58	0	0	1.28	8.00
7: Randomly Selected	5.93	18.37	25.25	7.32	57	0	0	1.28	8.01

Table 7-8 Average Values of Impact Metrics in Peak Hour with Five Times Nonmotorized Demand

	Avg. travel time (minutes)				**Number infeasible trips**			**Risk Score**	
Scenario	Auto.	Bike	Ped	Com. Avg.	Auto.	Bike	Ped	Bike	Ped
Base case (no block)	3.67	18.83	25.04	7.21	0	0	0	1.27	8.00
1: Min. Agency Cost	6.19	19.45	25.23	9.32	79	0	0	1.39	8.01
2: Min. Auto Time	6.02	19.45	25.23	9.18	63	0	0	1.39	8.01
3: Min. Ped Time	6.22	19.61	25.22	9.36	78	0	0	1.41	8.01
4: Min. Bike Time	6.02	19.45	25.23	9.18	63	0	0	1.39	8.01
5: Min. Total Cost	6.43	19.43	25.26	9.51	58	0	0	1.40	8.00
6: Min. Total Time	6.43	19.43	25.26	9.51	58	0	0	1.40	8.00
7: Randomly Selected	6.66	19.44	25.25	9.70	57	0	0	1.40	8.01

What if some motorized demand shift to nonmotorized (Demand Scenario 3)?

In demand scenarios with 50% existing motorized demand shifting to nonmotorized modes (in proportion to existing total bike and pedestrian demand) (Table 7-9), the average travel time for automobiles decreased by 10% in the base case and by approximately 40% in all maintenance scenarios. The average travel time for bikes increases only 8%, in all perspectives. During the maintenance period, shifting 50% from the automobile to a nonmotorized mode would bring 40% decrease in average automobile travel time while only leading to a 8% increase of in average bike travel time. Under higher demand scenarios, these impacts are expected to be exacerbated.The risk scores for pedestrians remain unchanged, while risk scores for bikes increases by approximately 3%. Only automobile-bike interactions were modeled. Thus, any impacts of changes in their flows on pedestrians is not captured.

Table 7-9 Average Values of Impact Metrics in Peak Hour with 50% Automobile Demand Shifts to Nonmotorized

	Avg. travel time (minutes)				**Number infeasible trips**			**Risk Score**	
Scenario	Auto.	Bike	Ped	Com. Avg.	Auto.	Bike	Ped	Bike	Ped
Base case (no block)	2.66	19.15	25.04	12.78	0	0	0	1.28	8.00
1: Min. Agency Cost	3.06	19.59	25.23	13.14	40	0	0	1.31	8.01
2: Min. Auto Time	3.04	19.57	25.23	13.13	31	0	0	1.31	8.01
3: Min. Ped Time	3.12	19.66	25.22	13.19	39	0	0	1.31	8.01
4: Min. Bike Time	3.04	19.57	25.23	13.13	31	0	0	1.31	8.01
5: Min. Total Cost	3.06	19.57	25.26	13.14	29	0	0	1.31	8.00
6: Min. Total Time	3.06	19.57	25.26	13.14	29	0	0	1.31	8.00
7: Randomly Selected	3.07	19.58	25.25	13.15	29	0	0	1.31	8.01

What if demand for all modes increase by 50% (Scenario 4)?

In demand scenarios in which all demand increases by 50%, average travel times increase dramatically for automobiles and bikes in the base case and all maintenance scenarios (Table 7-10). The average travel time for automobile users increases by approximately 150% in the base case and 300% in all maintenance scenarios. The average travel time for bike increases 23% and approximately 27% in the base case and in all maintenance scenarios, respectively. The risk scores for pedestrians remain unchanged, while risk scores for bikes increase by approximately 30%.

Average travel times for pedestrians are unchanged. It should be noted that the average travel times for automobiles in all maintenance perspectives are almost the same as for nonmotorized modes in all seven maintenance perspectives.

In addition, a demand scenario reflecting a combination of both scenarios 3 and 4 was explored. This scenario involves a 50% increase in demand across modes and 50% of the additional automobiles shifting to non-motorized modes. In this combined scenario (Table 7-11), the average travel time for automobiles increased by approximately 100 and 150% in the base case and under all maintenance perspectives, respectively. This travel time increase is much less than in the original demand increase case (about 150% and 300% increase in the base case and all maintenance scenarios, respectively). Additionally, the average travel time for bike increases 19 and 23% in the base case and in all the maintenance scenarios, respectively. This increase is also less than in the original demand increase case (23% and 27% in the base case and all maintenance perspectivesm respectively). The risk score changes for non-motorists are similar to those found in Scenario 4.

These results suggest that the capacity of nonmotorized infrastructure is not fully used in the base case as is often the case in smaller cities across the United States.

Table 7-10 Average Values of Impact Metrics in Peak Hour with 50% Increase of All Demand

	Avg. travel time (minutes)				Number infeasible trips			Risk Score	
Scenario	Auto.	Bike	Ped	Avg.	Auto.	Bike	Ped	Bike	Ped
Base case (no block)	7.47	21.77	25.04	8.20	0	0	0	1.65	8.00
1: Min. Agency Cost	22.19	23.04	25.23	22.27	119	0	0	1.66	8.01
2: Min. Auto Time	20.99	23.06	25.23	21.14	94	0	0	1.66	8.01
3: Min. Ped Time	21.81	23.46	25.22	21.93	116	0	0	1.66	8.01
4: Min. Bike Time	20.99	23.06	25.23	21.14	94	0	0	1.66	8.01
5: Min. Total Cost	23.99	23.01	25.26	24.00	88	0	0	1.65	8.00
6: Min. Total Time	23.99	23.01	25.26	24.00	88	0	0	1.65	8.00
7: Randomly Selected	25.03	22.99	25.25	24.99	86	0	0	1.65	8.01

Table 7-11 Average Values of Impact Metrics in Peak Hour with 50% increase in Demand and 50% of Additional Automobiles Shift to Nonmotorized

	Avg. travel time (minutes)				Avg. infeasible trips			Risk Score	
Perspectives	Auto.	Bike	Ped	Avg.	Auto.	Bike	Ped	Bike	Ped
Base case (no block)	6.01	21.05	25.04	9.28	0	0	0	1.65	8.00
1: Min. Agency Cost	13.31	22.22	25.23	15.31	99	0	0	1.65	8.01
2: Min. Auto Time	12.81	22.23	25.23	14.91	79	0	0	1.65	8.01
3: Min. Ped Time	13.37	22.55	25.22	15.39	97	0	0	1.66	8.01
4: Min. Bike Time	12.81	22.23	25.23	14.91	79	0	0	1.65	8.01
5:Min. Total Cost	14.02	22.21	25.26	15.89	73	0	0	1.65	8.00
6: Min. Total Time	14.02	22.21	25.26	15.89	73	0	0	1.65	8.00
7: Randomly Selected	14.73	22.21	25.25	16.46	72	0	0	1.65	8.01

DISCUSSION

Evaluation of results from the study of impacts of various maintenance plans across modes in a real-world study location indicate that maintenance actvitives impact travel times and for some users, even the feasibility of making a trip through the network. In general, automobile users are most impacted as they represent the majority of users (at 95% of the demand). However, the impacts on nonmotorized users depends on access and availability of links that are maintained. The evaluation showed that the specific schedules have less impact on travel times as compared with the numbers of activities. The impact of the activities varies by mode and has signficant consequences. The consequences extend beyond the impacts to automobilies.

There is significant reserve capacity to accommodate pedestrians and bicyclists, indicating that incentives to use non-motorized modes of transportation during maintenance and reconstruction might be desirable.

Other more extensive networks and networks with more non-motorized users should be explored and then guidelines developed for when disruptions should be considered in the selection and scheduling of projects.

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CHAPTER 8

Heuristic for Scheduling and Selecting Repair Alternatives for Multi Modal Transportation Facilities

PROBLEM STATEMENT

Non-motorized transportation facilities, bicycle paths and lanes, and sidewalks, have received more attention as communities promote sustainability and liveability. However, little attention has been given to how to schedule and coordinate the maintenance of these facilities. Furthermore, the maintenance of roads often disrupts access to these facilities and the users of non-motorized modes of transportation may experience a disproportionate increase in travel times.

Selecting and scheduling maintenance and repair can be formulated as an optimization problem, but agencies do not have the resources to run elaborate models. This chapter explores the use of some heuristics based on the robustness index to select and schedule maintenance and repair.

OBJECTIVE

The objective is to develop a heuristic based on simple analysis and rules to select and schedule maintenance and repair projects. Given a maintenance and rehabilitation options for each link in the network including shared and dedicated bicycle and pedestrian facilities, the heuristic aims to prioritize heavily utilized and important links. The methodology is modified from Liu et al. (2020) and is applied to a network based on the business district of Newark, Delaware.

OVERVIEW OF THE METHODOLOGY

The methodology uses a three-stage approach:

Stage 1**:** Identify the "criticality" of each link in the network based on the Network Robustness Index (NRI) (Scott et al., 2006, Liu et al., 2020). The Network Robustness Index is a measure of the increased delay if the link under consideration is removed from the system, and is considered to be an indication of the importance of the link in the network. This is intended to identify which links should be given priority in scheduling the repair/improvement. Other options to consider:

- Condition – links in poor condition may be an indicator of unsafe conditions or are likely to incur larger costs if repair/improvements are deferred.
- Usage – high usage links have a significant impact on users when they degrade.

An argument for using the NRI to indicate which links to repair first is that this will reduce network disruption in the future. The NRI also accounts for usage.

Stage 2**:** Select repair alternatives by incremental benefit cost analysis (Khisty et al., 2012). Having chosen the link on the basis of the NRI, we now select among the following alternatives:

1. Road only
2. Road and sidewalk

3. Road and bike
4. Road, bike and sidewalk
5. Bike only
6. Sidewalk only
7. Bike and sidewalk

Given that for our network the NRI is low for each bike and pedestrian link, options 5), 6) and 7) are not going to be high priorities. Furthermore, as most bike facilities are part of the roadway, options 3 and 4 are the only realistic options.

Assume you are going to complete the road repair (already selected), for options 1-4 you can calculate the costs and you assume that the NRI for each mode represents the benefit. Option 1, the auto mode represents the minimum acceptable b/c ratio. If the incremental benefit cost for other options exceeds this, then they should be completed. This approach is very conservative.

Table 8-1 shows illustrative data for a link. The threshold B/C is 0.009 (1.8/200). Options are ordered in terms of increasing cost, and you continue to invest while ever the incremental benefit cost ratio exceeds your threshold. In this case, auto, bike and pedestrian projects would be completed as the incremental benefit cost in each case exceeds the threshold.

Table 8-1 Example of Costs and Benefits for a Link

Mode	Incrementatl Cost of Improvement (000's $)	Robustness Index	Incremental Benefit Cost
Auto	200	1.8	
Bike	25	1.3	0.052
Pedestrian	40	1.2	0.03
Bike and Ped	65	1.5	0.023

Stage 3: The final step is to schedule the projects. In any year you complete as many links as you have budget.

DATA

The studied road network is located in Newark, DE (about 1 mile by 0.4 mile). Composed mainly by two-lane-wide arterials and local streets. The network is represented by 15 nodes for the auto mode and 17 nodes for the bike mode, and 34 links and 40 links respectively. The length of each link ranges from 0.1 to 0.4 miles and the average link length is 0.2 mile. The posted speed limit and the capacity are assumed as 25 mph and 1,600 passenger per hour per lane (for arterial) and 1,200 (for local street).

Travel speeds are represented by the BPR function. The BPR parameters and applied in the analysis is as shown in Table 8-2. Morning peak hourly OD demand is shown in Appendix A, Table A-A-4.

Table 8-2 BPR Parameters

Parameter	α	β
Arterial	0.6	5
Local Street	0.5	1

PROCESS

Stage 1: Identifying the Criticality of Each Link

Computing the Robustness Index

The first step is to compute the Robustness Index for each link under full and partial closure. The seSUE software (Ahipaşaoğlu et al., n.d.) is used to determine the total travel in the network. The software uses the Floyd-Warshall Algorithm based on the work of Dial (1971) to generate potential paths through the network based on the shortest distances between nodes.The deterministic user equilibrium is obtained by using the iteration method of successive average (MSA and the travel time for each OD pair computed. The user travel time is then multiplied by each OD demand and summed to get the total travel time in the network. This value is the base for comparison.

Capacity reductions of 50% or 100% are set for each link to simulate the effect of partial or full closure of each link and obtain the additional travel time compared with the travel time using the original network. For the links with one lane only, the capacity can be only reduced to 0% (100% reduction).

Table 8-3 presents the incremental cost (as represented by the increased travel time) of full or partial closure of each link for each of the three modes. This incremental cost is the Robustness Index for each link. The following assumptions are made:

- Vehicle mode
- For the links with more than one lane, the incremental cost is computed both under partial and full closure. However, these links are only assumed in partial closure during the maintenance projects in this study. The percentage of the travel time increase represents a measure of the importance of a link.
- Bike mode:
- The speed of cycling is assumed as 10 mph (based on Google estimation rules for estimating cycling travel time) and the capacity has remained unchanged. That is, it is assumed that only distance matters ($\alpha=0$, $\beta=1$) and only full closure to bicycles is possible.
- Pedestrian mode:
- The speed of pedestrians is assumed as 3 mph and the capacity has remained unchanged. The rest of the assumptions are the same as bike mode.

Table 8-3 Incremental Cost of Full / Partial Closure for Three Modes

Link	Road Type	Auto Mode					Bike mode		Pedestrian mode	
		Lanes	Full Closure		Partial Closure		Full Closure		Full Closure	
			Flow*Cost	Increment (%)	Flow*Cost	Increment (%)	Flow*Cost	Increment (%)	Flow*Cost	Increment (%)
Initial	--	--	425.43	--	425.43	--	20.67	--	59.39	--
1-2	Arterial	1	644.43	51.48	--	--	21.37	3.34	59.59	0.33
1-4	Arterial	1	495.93	16.57	--	--	21.48	3.88	59.78	0.65
2-1	Arterial	1	471.91	10.92	--	--	21.07	1.90	59.59	0.33
2-3	Arterial	1	546.22	28.39	--	--	21.41	3.58	59.50	0.19
2-7	Local Street	1	553.94	30.21	--	--	20.87	0.93	59.74	0.58
3-2	Arterial	1	498.18	17.10	--	--	20.96	1.38	59.50	0.19
3-9	Arterial	3	537.85	26.43	425.81	0.09	22.10	6.88	59.99	1.00
4-1	Arterial	1	493.50	16.00	--	--	21.78	5.37	59.78	0.65
4-10	Arterial	1	452.02	6.25	--	--	21.90	5.91	59.48	0.15
5-4	Arterial	2	1,045.40	145.73	439.55	3.32	22.61	9.37	59.62	0.39
5-11	Local Street	1	471.34	10.79	--	--	21.53	4.16	59.42	0.05
6-5	Arterial	2	1,895.83	345.63	445.55	4.73	24.24	17.27	59.74	0.58
6-12	Local Street	1	437.19	2.76	--	--	21.05	1.84	59.65	0.44
7-2	Local Street	1	474.22	11.47	--	--	20.77	0.45	59.40	0.02
7-6	Arterial	2	2,745.86	545.43	455.97	7.18	25.36	22.65	59.71	0.52
7-13	Local Street	1	460.87	8.33	--	--	21.07	1.93	59.50	0.18
8-7*	Arterial	2	3,286.26	672.45	469.99	10.47	24.91	20.49	60.12	1.22
							23.25	12.46	59.56	0.28
8-14	Local Street	1	434.43	2.12	--	--	20.73	0.29	59.40	0.02
9-8	Arterial	2	1,816.72	327.03	449.43	5.64	22.87	10.63	59.94	0.92
9-3	Arterial	3	527.26	23.94	425.81	0.09	21.65	4.73	59.99	1.00
9-15	Arterial	2	456.95	7.41	425.54	0.03	21.27	2.90	59.45	0.09
10-4	Arterial	1	436.65	2.64	--	--	21.01	1.64	59.48	0.15
10-11	Arterial	2	812.19	90.91	432.92	1.76	22.45	8.59	59.59	0.32
11-5	Local Street	1	435.04	2.26	--	--	20.91	1.16	59.42	0.05
11-12	Arterial	2	1,085.88	155.24	435.44	2.35	20.88	1.02	59.66	0.45

12-6	Local Street	1	432.28	1.61	--	--	23.49	13.61	59.40	0.02
12-13	Arterial	2	1,444.12	239.45	441.98	3.89	24.21	17.09	59.65	0.44
13-7	Local Street	1	501.41	17.86	--	--	21.14	2.26	59.50	0.18
13-14 *	Arterial	2	3,261.05	666.53	460.25	8.19	22.95	11.00	59.95	0.94
							21.11	2.10	59.72	0.55
14-8	Local Street	1	451.94	6.23	--	--	22.01	6.47	59.40	0.02
14-15	Arterial	2	1,794.83	321.89	443.69	4.29	22.86	10.59	59.61	0.36
15-9	Arterial	2	579.98	36.33	448.04	5.31	22.84	10.50	59.45	0.09
2-16	Bikeway	--	--	--	--	--	20.91	1.13	60.19	1.34
16-2	Bikeway	--	--	--	--	--	20.95	1.32	60.19	1.34
16-17	Bikeway	--	--	--	--	--	20.88	0.98	60.64	2.10
17-16	Bikeway	--	--	--	--	--	25.17	21.74	60.64	2.10
14-17	Ped.	--	--	--	--	--	--	--	59.72	0.55
15-14	Ped.	--	--	--	--	--	--	--	59.61	0.36
16-8	Ped.	--	--	--	--	--	--	--	60.12	1.22
17-13	Ped.	--	--	--	--	--	--	--	59.95	0.94

* two links in bike and pedestrian mode: link 8-7 represents link 8-16 and 16-7; link 13-14 represents link 13-17 and 17-14

The Importance Rank of the Links

From Table 8-3, the traffic impact on auto, bike, and pedestrian mode, in terms of additional travel time, is comprehensively studied. The links can be rearranged based on the scale of this impact. For auto mode, out of 32 link segments, there are 14 links with more than one lane (i.e, multi-lane link). It is observed that full closure results in larger traffic impact than partial closure in these links. Therefore, when considering the maintenance in multi-lane links, partial closure is a more realistic strategy to reduce the impact. Moreover, comparing the initial system traffic flowcost in three modes, the auto mode takes major account for the system. Based on this, the importance of the links in this study is arranged by the scale of the traffic impact of partial closure in multi-lane links and full closure in single-lane links in auto mode. Table 8-4 shows the importance of the link based on this consideration.

Table 8-4 The Importance Rank of the Links

Link	Link type	% of traffic impact	Importance	Link	Link type	% of traffic impact	Importance
1-2	single-lane	51.48	1	9-8	multi-lane	5.64	17
2-7	single-lane	30.21	2	15-9	multi-lane	5.31	18
2-3	single-lane	28.39	3	6-5	multi-lane	4.73	19
13-7	single-lane	17.86	4	14-15	multi-lane	4.29	20
3-2	single-lane	17.10	5	12-13	multi-lane	3.89	21
1-4	single-lane	16.57	6	5-4	multi-lane	3.32	22
4-1	single-lane	16.00	7	6-12	single-lane	2.76	23
7-2	single-lane	11.47	8	10-4	single-lane	2.64	24
2-1	single-lane	10.92	9	11-12	multi-lane	2.35	25
5-11	single-lane	10.79	10	11-5	single-lane	2.26	26
8-7	multi-lane	10.47	11	8-14	single-lane	2.12	27
7-13	single-lane	8.33	12	10-11	multi-lane	1.76	28
13-14	multi-lane	8.19	13	12-6	single-lane	1.61	29
7-6	multi-lane	7.18	14	3-9	multi-lane	0.09	30
4-10	single-lane	9.39	15	9-3	multi-lane	0.09	31
14-8	single-lane	6.23	16	9-15	multi-lane	0.03	32

Stage 2: Prioritize the Repair Options

From Appendix D, **Error! Reference source not found.**, 50 proposed maintenance projects are composed of 36 projects in 3 types of pavement maintenance, 10 pedestrian and 4 bike lane reconstruction projects for assigned links based on the evaluated conditions.

Table 8-5 to Table 8-7 present the suggested maintenance sequence based on the importance of link shown in Table 8-4 for pavement reconstruction projects with sidewalk projects (Table 8-5), major repair with sidewalk project (Table 8-6), and minor repair with sidewalk and bicycle projects (Table 8-7). Although sidewalk and bike lane reconstruction projects may proceed independently, it will be more efficient to bundle together with planned pavement projects if they are geographically adjacent.

Figure 8-1 shows the accumulated traffic impact in percentage along with accumulated overall maintenance cost. It is worth noting that although the cost of minor pavement repair either with or without pedestrian and bike reconstruction projects is far less than the rest of the maintenance scenario, the traffic impact is relatively larger than the other two. It may be attributed to the single-lane links with higher rank of importance.

Table 8-5 Suggested Order for Pavement Reconstruction

Link	Link type	Importance	Suggested order	Auto		Bike		Pedestrian		Reconstruction 1 (pavement)				Reconstruction 2 (pedestrian)			
				traffic impact	% of traffic impact	traffic impact	% of traffic impact	traffic impact	% of traffic impact	Duration (days)	Cost	Project index	% of traffic impact	Duration (days)	Cost	Project index	% of traffic impact
1-4	single	6	1	496	16.57	21.48	3.88	59.78	0.65	2	$148,249	0	33.14	3	$39,961	38	1.95
4-1	single	7	2	493	16.00	21.78	5.37	59.78	0.65	2	$148,249	1	32.00	3	$39,961	39	1.95
5-11	single	10	3	471	10.79	21.53	4.16	59.42	0.05	2	$114,556	2	21.58	--	--	--	--
6-12	single	23	4	437	2.76	21.05	1.84	59.65	0.44	2	$101,079	4	5.53	--	--	--	--
11-5	single	26	5	435	2.26	20.91	1.16	59.42	0.05	2	$114,556	3	4.52	--	--	--	--
12-6	single	29	6	432	1.61	23.49	13.61	59.40	0.02	2	$101,079	5	3.22	--	--	--	--
3-9	multi	30	7	426	0.09	22.10	6.88	59.99	1.00	6	$510,714	6	0.54	3	$42,064	42	3.00
9-3	mult	31	8	426	0.09	21.65	4.73	59.99	1.00	6	$510,714	7	0.54	3	$42,064	43	3.00

Table 8-6 Suggested Order for Pavement Major Repair and Pedestrian Facility Reconstruction

Link	Link type	Importance	Suggested order	Auto		Bike		Pedestrian		Major repair (pavement)				Reconstruction 2 (pedestrian)			
				traffic impact	% of traffic impact	traffic impact	% of traffic impact	traffic impact	% of traffic impact	Duration (days)	Cost	Project index	% of traffic impact	Duration (days)	Cost	Project index	% of traffic impact
8-7	multi	11	1	470	10.47	24.91	20.49	59.72	0.55	1	$76,032	13, 14	10.47	--	--	--	--
13-14	multi	13	2	460	8.19	22.95	11.00	59.72	0.55	3	$190,080	20, 21	24.56	--	--	--	--
7-6	multi	14	3	456	7.18	25.36	22.65	59.71	0.52	1	$152,064	12	7.18	--	--	--	--
9-8	multi	17	4	449	5.64	22.87	10.63	59.94	0.92	3	$228,096	15,16	16.92	--	--	--	--
15-9	multi	18	5	448	5.31	22.84	10.50	59.45	0.09	2	$152,064	9	10.63	3	$42,064	45	0.28
6-5	multi	19	6	446	4.73	24.24	17.27	59.74	0.58	1	$76,032	11	4.73	--	--	--	--
14-15	multi	20	7	444	4.29	22.86	10.59	59.61	0.36	4	$266,112	22,23	17.17	--	--	--	--
12-13	multi	21	8	442	3.89	24.21	17.09	59.65	0.44	1	$76,032	19	3.89	--	--	--	--
5-4	multi	22	9	440	3.32	22.61	9.37	59.62	0.39	2	$139,392	10	6.64	--	--	--	--
11-12	multi	25	10	435	2.35	20.88	1.02	59.66	0.45	1	$76,032	18	2.35	--	--	--	--
10-11	multi	28	11	433	1.76	22.45	8.59	59.59	0.32	2	$152,064	17	3.52	--	--	--	--
9-15	multi	32	12	426	0.03	21.27	2.90	59.45	0.09	2	$152,064	8	0.05	3	$42,064	44	0.28

Table 8-7 Suggested Order for Pavement Minor Repair, Pedestrian and Bikeway Reconstruction

Link	Link type			Auto		Bike		Pedestrian		Minor repair (pavement)				Reconstruction 2 (pedestrian)				Reconstruction 3 (bikeway)			
		Importance	Suggested order	traffic impact	% of traffic impact	traffic impact	% of traffic impact	traffic impact	% of traffic impact	Duration (days)	Cost	Project index	% of traffic impact	Duration (days)	Cost	Project index	% of traffic impact	Duration (days)	Cost	Project index	% of traffic impact
1-2	single	1	1	644	51.48	21.36	3.34	59.59	0.33	1	$33,635	24	51.48	5	$84,128	36	1.64	--	--	--	--
2-7	single	2	2	554	30.21	20.87	0.93	59.74	0.58	1	$25,226	32	30.21	--	--	--	--	--	--	--	--
2-3	single	3	3	546	28.39	21.41	3.58	59.50	0.19	1	$50,452	26	28.39	8	$126,192	40	1.50	1	$37,664	46	3.58
13-7	single	4	4	501	17.86	21.14	2.26	59.50	0.18	1	$8,409	35	17.86		--	--	--	--	--	--	--
3-2	single	5	5	498	17.10	20.96	1.38	59.50	0.19	1	$50,452	27	17.10	8	$126,192	41	1.50	1	$37,664	47	1.38
1-4	single	6	6	496	16.57	21.48	3.88	59.78	0.65	1	$15,977	28	16.57	--	--	--	--	--	--	--	--
4-1	single	7	7	493	16.00	21.78	5.37	59.78	0.65	1	$15,977	29	16.00	--	--	--	--	--	--	--	--
7-2	single	8	8	474	11.47	20.77	0.45	59.40	0.02	1	$25,226	33	11.47	--	--	--	--	--	--	--	--
2-1	single	9	9	472	10.92	21.07	1.90	59.59	0.33	1	$33,635	25	10.92	5	$84,128	37	1.64	--	--	--	--
7-13	single	12	11	461	8.33	21.07	1.93	59.50	0.18	1	$8,409	34	8.33	--	--	--	--	--	--	--	--
4-10	single	15	10	452	6.25	21.90	5.91	59.48	0.15	1	$10,090	30	6.25	--	--	--	--	1	$18,832	48	5.91
10-4	single	24	12	437	2.64	21.01	1.64	59.48	0.15	1	$10,090	31	2.64	--	--	--	--	1	$18,832	49	1.64

Figure 8-1 Accumulated Traffic Impact versus Accumulated Overall Maintenance Cost

To illustrate the process, consider link 1-4, noting that the analysis is similar for link 4-1. For any link the incremental benefit cost analysis requires that the incremental benefit cost ratio is greater than or equal to the minimum benefit cost ratio for all pavement projects, which are the default projects. The benefit is interpreted as the future disruption avoided and is computed as the product of the number of days, and the sum of the auto and bicycle traffic impact, as both the bicycle the auto traffic uses the pavement. The minimum benefit cost ratio for the pavement projects listed in Table 8-5, Table 8-6, and Table 8-7 is 0.00004, a major repair project for link 9-15. This is the threshold used for the incremental benefit cost analysis.

The process begins by ordering the potential projects by the level of investment and assembling the data for the costs and benefits as measured by the percentage of the traffic impact. The incremental cost and incremental benefit of each project compared to the project involving the lesser investment is computed and the incremental benefit cost ratio is computed. If the incremental benefit cost ratio is greater than the threshold then the project is accepted and the next increment of investment is considered. If the value is not greater than the threshold the project involving the lesser investment is selected. If there are no additional investment options then the analysis ends with the activity involving the highest level of investment for which the incremental benefit cost ratio exceeds the threshold. The calculations for link 1-4 are shown in Table 8-8. Based on this analysis the best option for link 1-4 is reconstruction including pedestrian facilities.

For the case study, the additional investment is selected for each link. The next step is to schedule the projects.

Table 8-8 Illustrative Incremental Benefit Cost Analysis for Link 1-4

Option	Cost	% of Traffic Impact (Benefit)	Benefit Cost Ratio	Incremental Cost	Incremental % of Traffic Impact (Incremental Benefit)	Incremental Benefit Cost Ratio	Notes
Minor Repair – pavement only	$15, 977	20.45	0.00128				
Reconstruction – pavement only	$148, 249	40.9		$132,272	20.45	0.00015	Exceeds threshold
Reconstruction – pavement and pedestrian	$188,210	42.85		$39, 961	1.95	0.00005	Exceeds threshold

Table 8-9 Link Activities Selected Using the Incremental Benefit Cost Ratio

Importance	Link	Link type	% of traffic impact	Activity
1	1-2	single-lane	51.48	Minor repair including sidewalks
2	2-7	single-lane	30.21	Minor repair
3	2-3	single-lane	28.39	Minor repair including bike and ped
4	13-7	single-lane	17.86	Minor repair
5	3-2	single-lane	17.10	Minor repair including bike and ped
6	1-4	single-lane	16.57	Reconstruction including sidewalks
7	4-1	single-lane	16.00	Reconstruction including sidewalks
8	7-2	single-lane	11.47	Minor repair
9	2-1	single-lane	10.92	Minor repair including sidewalks
10	5-11	single-lane	10.79	Reconstruction
11	8-7	multi-lane	10.47	Major repair
12	7-13	single-lane	8.33	Minor repair
13	13-14	multi-lane	8.19	Major repair
14	7-6	multi-lane	7.18	Major repair
15	4-10	single-lane	9.39	Minor repair including bicycle
16	14-8	single-lane	6.23	No activity
17	9-8	multi-lane	5.64	Major repair
18	15-9	multi-lane	5.31	Major repair
19	6-5	multi-lane	4.73	Major repair
20	14-15	multi-lane	4.29	Major repair
21	12-13	multi-lane	3.89	Major repair
22	5-4	multi-lane	3.32	Major repair
23	6-12	single-lane	2.76	Reconstruction
24	10-4	single-lane	2.64	Minor repair including bicycle
25	11-12	multi-lane	2.35	Major repair
26	11-5	single-lane	2.26	Reconstruction
27	8-14	single-lane	2.12	No activity
28	10-11	multi-lane	1.76	Major repair
29	12-6	single-lane	1.61	Reconstruction
30	3-9	multi-lane	0.09	Reconstruction including sidewalks
31	9-3	multi-lane	0.09	Reconstruction including sidewalks
32	9-15	multi-lane	0.03	Major repair with sidewalks

Stage 3: Scheduling

Using an annual budget of $0.55 million, projects are assigned to each year in the order of important shown in Table 8-9 until the budget is exhausted for that year. Any remaining budget can either be carried forward to the following year or is lost. If budget is lost the remaining projects should be scanned to determine the highest ranked project that can be accomplished with the remaining budget. The schedule and cumulative expenditures using both assumptions are shown in Table 8-10. With carry over, all projects are completed. In the case of no carryover the projects on links 9-3 and 3-9 (ranked 30 and 31) are never completed as the cost exceeds the annual budget.

Table 8-10 Scheduling of Projects

Importance	Link	Activity	Project Cost	Year Undertaken (Carryover)	Year Undertaken (No Carryover)
1	1-2	Minor repair including sidewalks	$117,763	1	1
2	2-7	Minor repair	$25,226	1	1
3	2-3	Minor repair including bike and ped	$214,308	1	1
4	13-7	Minor repair	$8,409	1	1
5	3-2	Minor repair including bike and ped	$214,308	2	2
6	1-4	Reconstruction including sidewalks	$15,977	2	1
6	1-4	Reconstruction including sidewalks	$320,482	2	3
7	4-1	Minor repair	$15,977	2	1
7	4-1	Minor repair including sidewalks	$320,482	3	4
8	7-2	Reconstruction	$25,226	3	1
9	2-1	Major repair	$117,763	3	2
10	11-5	Minor repair	$114,556	4	2
11	8-7	Major repair	$76,032	4	1
12	7-13	Major repair	$8,409	4	2
13	13-14	Minor repair including bicycle	$190,080	4	5
14	7-6	No activity	$152,064	4	3
15	4-10	Major repair	$28,922	4	2
17	9-8	Major repair	$228,096	5	5
18	15-9	Major repair	$194,128	5	6
19	6-5	Major repair	$76,032	5	4
20	14-15	Major repair	$266,112	6	6
21	12-13	Major repair	$76,032	6	4
22	5-4	Reconstruction	$139,392	6	6
23	12-6	Minor repair including bicycle	$101,079	7	7
24	10-4	Major repair	$28,922	7	5
25	11-12	Reconstruction	$76,032	7	7
26	5-11	No activity	$114,556	7	7
28	10-11	Major repair	$152,064	7	7
29	6-12	Reconstruction	$101,079	8	8
30	9-3	Reconstruction including sidewalks	$552,778	9	
31	3-9	Reconstruction including sidewalks	$552,778	10	
32	9-15	Major repair with sidewalks	$194,128	10	8

Figure 8-2 shows the cumulative expenditure by year. The no carryover option means that more projects are completed in the first eight years but the budget is not used in years 9 and 10. This is reinforrced by the cumulative traffic impacts shown in Figure 8-3. In reality a 10-year plan is likely to be adjusted and the no carryover option is a more efficient use of resources.

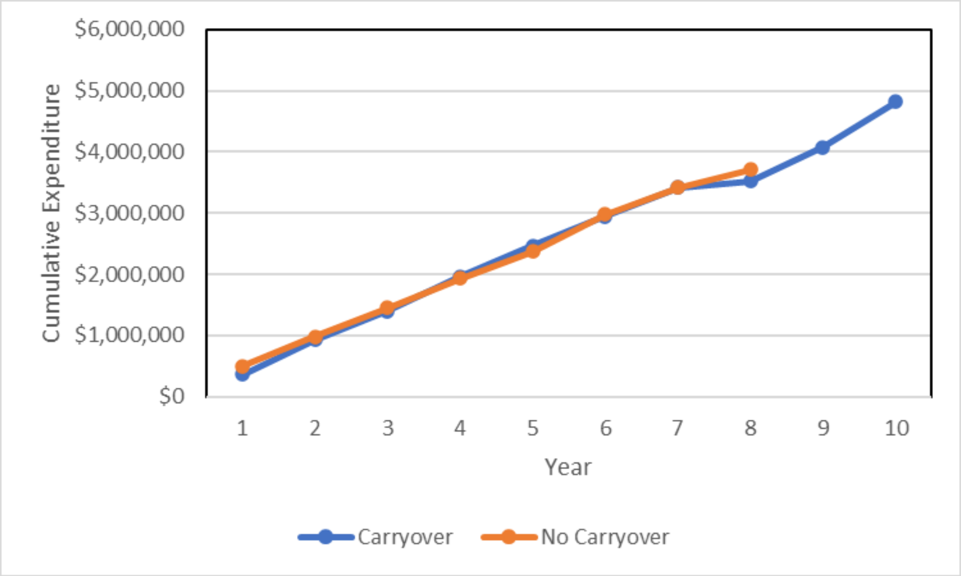

Figure 8-2 Cumulative Expenditures by Year

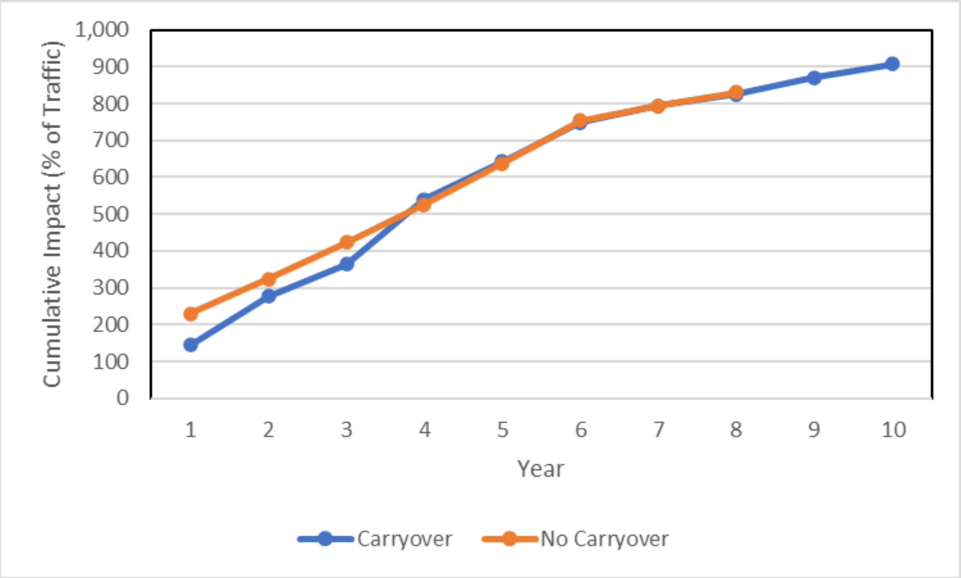

Figure 8-3 Cumulative Traffic Impact by Year

Discussion

Relative Disruption

However, we can also explore the relative disruptions to the different modes and in different years. Figure 8-4 shows the investment by year and by mode. The first two years include investements in all three modes but over the planning horizon, the projects are more focused on autos. Figure 8-5 shows the disruption for each mode and year. Given that projects are priortized by disruption, the projects in the later years are less disruptive.

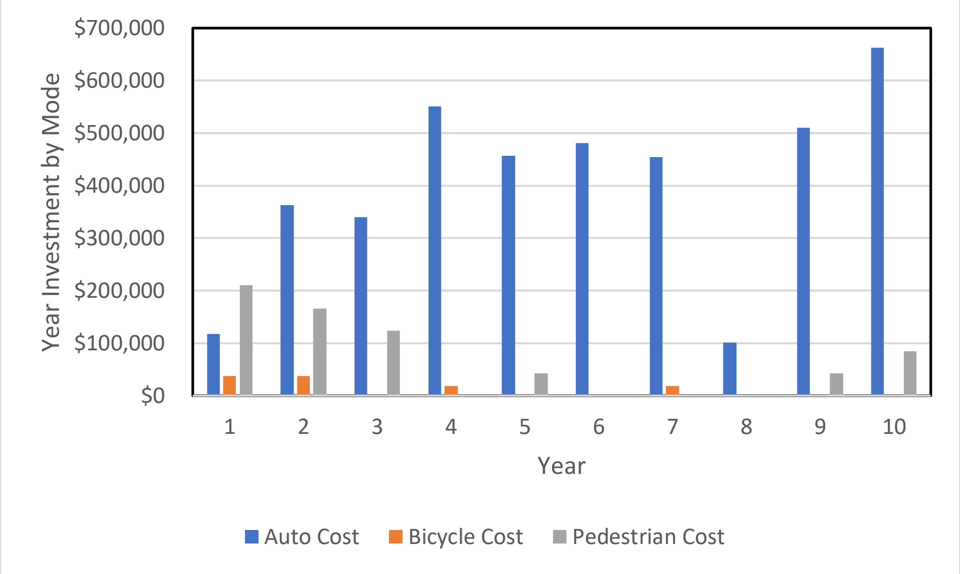

Figure 8-4 Investment by Mode and Year

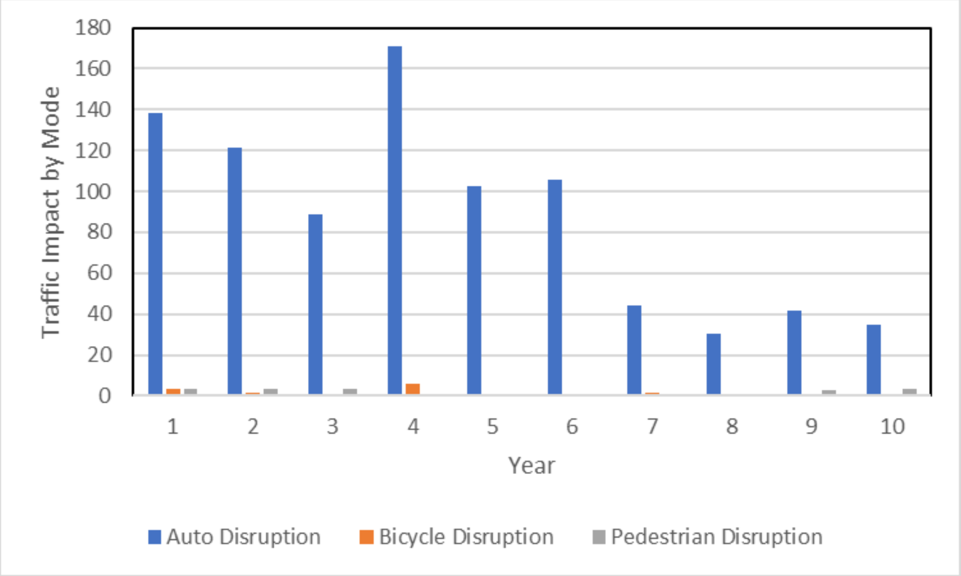

Figure 8-5 Disruption % by Mode and Year

Comparison with Project Bundles

The heuristic differs significantly from the project bundling described in Chapter 6 as the objectives differ. The focus is on avoiding potential future disruption. For comparison, Table 8-11 shows the average percentage increase in travel time and average number of infeasible trips for the seven perspectives (from Chapter 7) and the heuristic presented in this chapter. The heuristic also used a different routing algorithm that avoided infeasible trips but used a penalty function.

The heuristic performed as well as some of the perspectives that focused on specific modes.

Table 8-11 Average Values of Impact Metrics in Peak Hour for All Perspectives (Existing Demand)

	Avg. % increase in travel time				**Avg. infeasible trips**		
Perspective	Auto.	Bike	Ped	Com. Avg.	Auto.	Bike	Ped
Base case					0	0	0
1: Min. Agency Cost	77.70%	1.97%	0.76%	57.74%	79	0	0
2: Min. Auto Time	71.96%	1.97%	0.76%	53.54%	63	0	0
3: Min. Ped Time	75.68%	2.59%	0.72%	56.43%	78	0	0
4: Min. Bike Time	71.96%	1.97%	0.76%	53.54%	63	0	0
5: Min. Total Cost	85.81%	1.97%	0.88%	64.04%	58	0	0
6: Min. Total Time	85.81%	1.97%	0.88%	64.04%	58	0	0
7: Randomly Selected	93.58%	1.97%	0.84%	69.55%	57	0	0
Heuristic Base case					0	0	0
Heuristic	71.96%	1.97%	0.76%	53.54%	0	0	0

Table 8-12 shows the project bundles for the heuristic method using a similar format to Table 7-1 and Table 7-2. The bundling of projects differs significantly to the objectives and scenarios discussed in Chapter 7.

To highlight these differences the project schedule found using the heuristic is added to the bubble chart in Figure 7-1, as shown in Figure 8-6. In Figure 8-6, the projects selected using the heuristic are offset to the right of each year. Note that projects 24,25, 28 and 29 are not undertaken as these minor repair projects were replaced by reconstruction using the heuristic. Only eleven of fifty projects are scheduled in the same year as any of the projects from the investment scenarios presented in Chapter 7.

Table 8-12 Project Bundling Based on the Heuristic Method

	Heuristic Method
1	[26, 32,35,36,40,46]
2	[0,27,38,41,47]
3	[1,33,37,39]
4	[3,12,13,14,20,21,30,34,48]
5	[9,11,15,16,45]
6	[10,19,22,23]
7	[2,5,17,18,31,49]
8	[4]
9	[7,43]
10	[6,8,42,44]

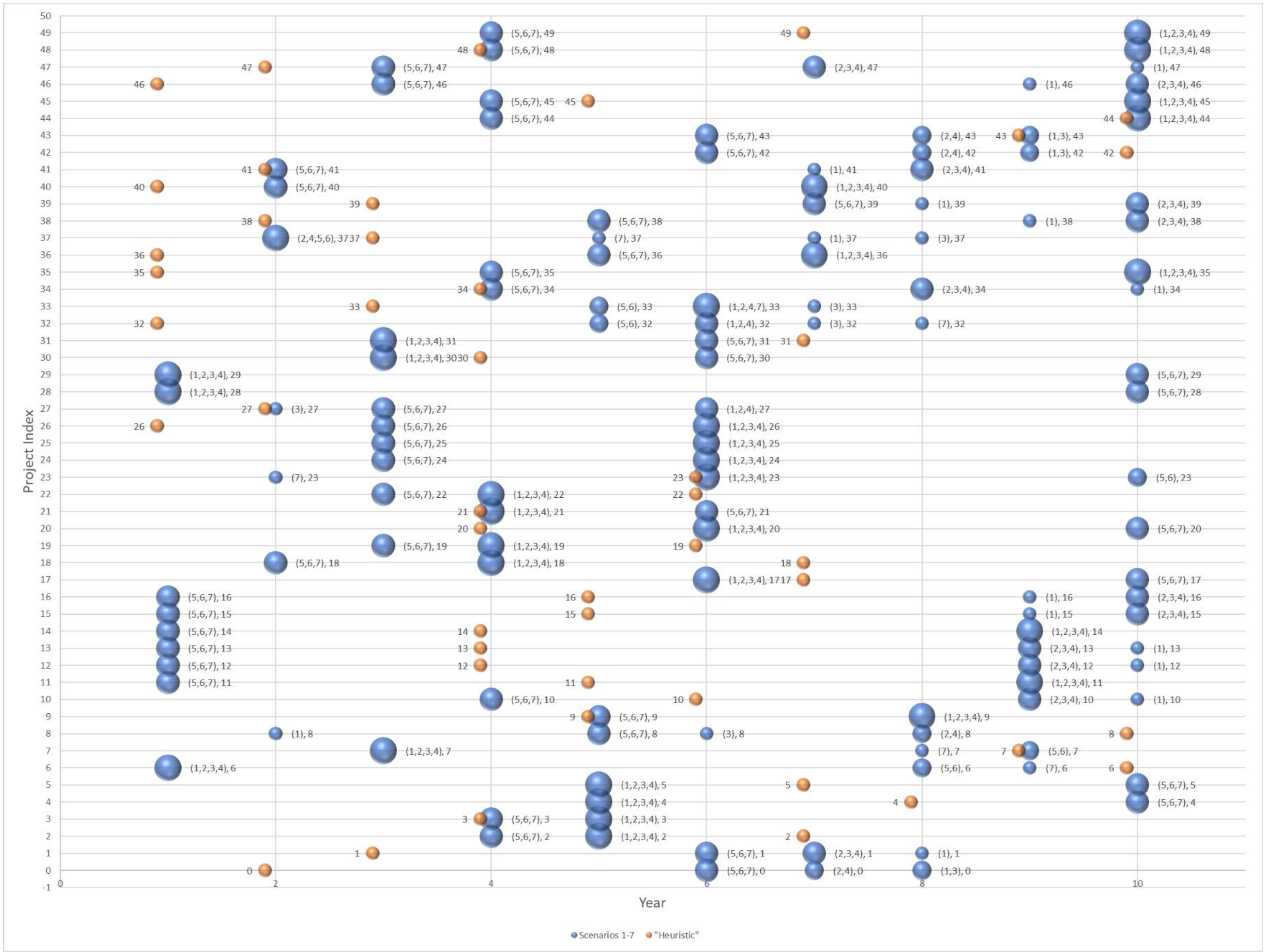

Figure 8-6 Projects Assigned Using Investment Scenarios 1-7 and the Heuristic.

To explore the common projects among the scenarios in another way, **Error! Not a valid bookmark self-reference.** shows the number of projects in common for each pair of scenarios. It is very clear that scenarios 1, 2, 3 and 4 are very similar and have the majority of projects scheduled in the same year. Likewise scenarios 5, 6 and 7 have many projects scheduled for the same year. Finally, the heuristic is unlike any of the scenarios.

Table 8-13 Number of Projects in Common in Each Pair of Investment Perspectives

	Perspective 2	Perspective 3	Perspective 4	Perspective 5	Perspective 6	Perspective 7	Heuristic
Perspective 1	33	33	33	0	0	1	4
Perspective 2		42	50	1	1	1	3
Perspective 3			42	0	0	0	5
Perspective 4				1	1	1	3
Perspective 5					50	44	6
Perspective 6						44	6
Perspective 7							5

SUMMARY

This chaper explored an alternative method to identify and schedule potential projects. The importance of each link was determined by computing the traffic impact of studied links under partial or full closure. The links with the greatest impact were considered to be most critical. All links were ordered by criticality. That is, the suggested repair order refers to the rank of the importance and the relationship between overall cost and traffic impact. The traffic impact increases significantly in the single-lane links with higher rank of importance. For links with multiple options for activities, either a more substanive pavement improvement or the improvement of the bicycle or pedestrian faciltiies, an incremental benefit cost analysis was used to select the best activity. Projects were schedule in order of importance subject to a budget constraint. For the example network, the investment in the pedestrian and bicycle facility improvements was always justified.

The heuristic differs significantly from the project bundling described in Chapter 6 as the objectives differ. This underscores the importance of considering different objectives and exploring the impacts for each of the modes.

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CHAPTER 9

Findings and Recommendations

SUMMARY

Case studies involving multi-objective, multi-attribute and multi-modal tradeoffs when infrastructure repairs and improvements are undertaken were developed. The case studies revealed the complexity of issues, the many different objectives, and the reliance on experience to integrate multi-objective, multi-attribute and multi-modal tradeoffs into decision related to mainteance programming.

An in-depth case study focusing on the emergency repair of the I-495 bridge in Delaware emphasized the importance of traffic control, traffic monitoring and communication in such cases. This case study also demonstrated resourcefulness, such as expediting the authority to complete work and resourcing materials from other projects, to reduce disruption.

The research then explored performance measures for shared auto, bicycle and pedestrian facilities. A network model of the Newark, Delaware business district was developed to understand the disruptions experienced by different modes. This network was then enhanced to capture more detail. The location was selected given team members familiarity with the location, and the fact that a major road reconstruction project had recently caused significant disruption to non-motorized modes (bicycling and walking).

Fifty candidate projects to be implemented over a 10-year period were identified for the network. These projects range from minor repair to full reconstruction as well as improvements to sidewalks and bicycle facilities. Using the network model and a fixed annual budget, strategies for bundling projects to enhance network performance were developed. Four different performance measures (agency costs, total costs, standard deviations of travel times) were used for each mode, and the problem was formulated as a multi-dimensional knapsack problem. Project bundles were developed using a genetic algorithm. For comparison, a heuristic method was developed to set project priorities and schedule projects.

Seven different investment perspectives and five different demand scenarios were evaluated. The results showed that the project schedule was similar for scenarios focusing on minimizing agency costs or travel times for any mode, and for scenaios using a weighted combination of travel times, or travel times and agency costs, and a random selection of projects. Furthermore, increases in demand can be accommodated by non-motorized modes.

The research showed that:

- User delays due to maintenance are significant for non-motorized modes.
- Modeling the networks and their interactions is non-trivial.
- Users of different modes bear a disproportionate share of disruptions costs and mobility impaired users are even further inconvenienced.

While agencies are required to accommodate pedestrians and bicyclists during road reconstruction, paving and maintenance, in practice there are many examples where users are inconvenienced. Like the I-495 bridge reconsturuction project, all projects need to consider strategies for controlling traffic, monitoring the impacts and delays, and communicating the changes as the project proceeds.

RECOMMENDATIONS

This project demonstrated the importance of agencies paying attention to the disruption caused to all modes of transportation. Increased interest in non-motorized modes of transportation as a strategy to support sustainable mobility and accesss is slowly encouaging more users and the mode share of non-motorized modes and becoming signficiant. Bicycle and pedestrian facilities have been shown to contribute to the changes. However, long term success requires consideration of how the facilties will be maintained, and how to mitigate the disruptions that will occur when shared facilities are maintained or improved.

This can be accomplished by:

- Raising awareness of the issues through workshops, and presentations. There are two audiences:
    - Organizations actively selecting, managing and implementing improvement projects. These organizations include state departments of transportation, consultants and contractors
    - Organizations promoting active and non-motorized transportation. These organizations include state departments of transportation, Metropolitan Planning Organzations (MPOs), advocacy organizations such as Complete Streets, and Smart Growth.
- Including consideration of disruption to all modes in the lifecycle analysis of all assets.
- Integrating non-motorized facilities into asset management plans. Only Minnesota included pedestrian assets in their 2019 Transporatation Asset Management Plan. Connecticut was considering included pedestrian assets in their 2022 submission. However, some other states (for example, California) have asset management plans for non-motorized assets. While the requirement is that only pavements and bridges on the National Highway System are included in the plans, understanding what a plan, whether part of the federal submission or for internal use, might look like is of value.

OPPORTUNITIES FOR FUTURE RESEARCH

This project has also identified opportunities for future research. These opportunities fall into three areas: improving the models, addressing equity, and communicating the issues.

Improving the Models

Models were used in this research to estimated the disruption caused to users of different modes. This required using a basic four-step transportation modeling framework where the last step involves route selection. Limitations of the existing models include:

- Understanding how the attributes of facilities for non-motorized modes impact demand. In a multi-modal network, demand elasticity involves the elasticity of each O-D demand quantity and the demand of each mode/mode combination in one O-D. In this study, the O-D demand of every single mode is assumed fixed, and no demand elasticity is considered. This unrealistic assumption is made because of the limitation of data availability and for the purpose of simplicity. The solution space would expand dramatically after adding the dimension of modes and their combinations. Problems of this type with small scale are still solvable nowadays. However, no research is found for solving a such problem on a big city scale.
- Enhancing network representations to capture inconveniences and disruptions. In this research, the trip travel time is the only utility function used in traffic assignment. However, many factors impact individual travel decisions, such as convenience, monetary cost, safety, health, and environmental concerns. A lot of survey work is needed to extract travelers' preferences in trip decision-making. Alternatively, if the travelers are classified with some relevant attributes, e.g., income, education level, and occupation. A specific utility function may be constructed for each class and it will help in modeling trip decisions in traffic assignments and impact evaluation.

- Recognizing the impact of shared modes on link performance functions. The study of travelers of different modes using a shared link facility is still quite immature. Treating travelers homogenously is reasonable occasionally, as in the sharrows-bike-lanes case in this research. However, a more generous condition is that modes of different uses change the speed in the presence of others, and homogenous traffic flow theory may not apply in this case. The agent-based simulations that treat each traveler as an agent may provide a good complementary approach, while the computation complexity would increase dramatically as well.
- Capturing mode shifts en route when one or more modes are disrupted. Traffic assignment problem considering two combined modes, e.g., park-and-ride is solvable for small or medium problems. However, in the case study in this project, four modes are involved and trips pattern with combined modes are much more complex than park-and-ride. Traditionally approach is to model the traffic assignment problem as a variational inequality problem. However, the solution space expands exponentially with the number of modes in a multi-modal network. Metaheuristic algorithms may be a good method to get a good enough solution for practical purposes.
- Selecting projects to reflect the many tradeoffs involved including integrating into a lifecycle planning analysis. In this study, Pareto fronts generated by NSGA-II are used to demonstrate the effect of different bundling plans on transportation infrastructure users and agency costs. However, the current analysis does not consider several costs that could happen in the lifecycle of the transportation infrastructure (e.g., accident cost). For future studies, integrating the project selection/bundling process into a lifecycle planning analysis would be a way to improve the current framework. Feedback on post-implementation effects could help NSGA-II to explore better lifecycle solutions.
- Considering infrastructure condition deterioration over the planning horizon. Transportation infrastructure condition continues to deteriorate without M&R actions. Postponing the M&R actions may incur higher costs to achieve the desired condition or service performance. In this study, the projects are allowed to be scheduled at any time during the 10-year horizon without considering the costs associated with the infrastructure condition deterioration. In futures study, age-related infrastructure condition models need to be incorporated to improve the current NSGA-II.
- Scaling the project bundling methodology to large networks. In this study, the most time-consuming step in NSGA-II is the travel-time evaluation. For large networks that usually contain more travel routes and users, it could be even more computationally expensive to calculate the travel times for different modes of users as to a local network as this project presented. The computational time required by the NSGA-II to yield a near-optimal solution goes up exponentially. Neural Networks (NN) would be a promising alternative to estimate the travel times in large networks than the current evaluation method.
- Improving the project bundling assumptions. In this study, there is a steady annual construction budget limit over the planning horizon for simplicity. However, a dynamic annual construction budget limit may help NSGA-II to explore better bundling plans. Moreover, this study assumes that there is only one set of equipment available for each action category, which is also a simplification. In future studies, considering simultaneous projects based on the actual availability of the equipment by agencies and contractors could be another way to improve the current analysis.

Addressing Equity

While we considered equity issues among modes and for special types of users, such as mobility impaired, it is not clear how to assess equity and integrate the assessment into the decision making process. Should equity be a constraint or an objective?

Communicating the Issues

The recommendations suggested raising awareness through workshops and presentations. Further research is needed to understand the audience, the content and the best delivery mechanism.

APPENDIX A

Link and O-D Data for Example Network

This Appendix includes link usage data for autos, pedestrians and bicycles Table A-1, Table A-2 and Table A-3 for the network described in Chapter 3. This data is inferred from limited counts taken by students over a period of multiple years. It is intended to be realistic but not real. This data was used to infer origin-destination matrices based on expert judgement. The data is included in Table A-4 and is intended to be realistic but not real.

Table A-A-1 Link Usage – Auto (vehicles per hour per lane)

Link	Street name	Dir	#lanes	7pm-7am	7am-10am	10am-3pm	3pm-7pm
1-2	E. Cleveland St.	EB	1	400	1600	1000	1600
		WB	1	400	1600	1000	1600
1-4	N. College Ave.	NB	1	400	1600	1000	1600
		SB	1	400	1600	1000	1600
2-3	E. Cleveland St.	EB	1	400	1600	1000	1600
		WB	1	400	1600	1000	1600
2-7	N. Chapel St.	NB	1	300	1200	700	1200
		SB	1	300	1200	700	1200
2-16	Pomeroy Trail	NB					
		SB					
3-9	Capital Tr.	NB	3	400	1600	1000	1600
		SB	3	400	1600	1000	1600
4-5	E. Main St.	WB	2	400	1600	1000	1600
4-10	S. College Ave.	NB	1	400	1600	1000	1600
		SB	1	400	1600	1000	1600
5-6	E. Main St.	WB	2	400	1600	1000	1600
5-11	Academy St.	NB	1	200	800	500	800
		SB	2	200	800	500	800
6-7	E. Main St.	WB	2	400	1600	1000	1600
6-12	Haines St.	NB	1	50	200	100	200
		SB	1	50	200	100	200
7-13	S. Chapel St.	NB	1	300	1200	700	1200
		SB	1	300	1200	700	1200
7-16	E. Main St.	WB	2	400	1600	1000	1600
8-9	E. Main St.	WB	2	400	1600	1000	1600
8-14	Tyre Ave.	NB	1	50	200	100	200
		SB	1	50	200	100	200
8-16	E. Main St.	WB	2	400	1600	1000	1600
9-15	Library Ave.	NB	2	400	1600	1000	1600
		SB	2	400	1600	1000	1600
10-11	Delaware Ave.	EB	2	400	1600	1000	1600
11-12	Delaware Ave.	EB	2	400	1600	1000	1600
12-13	Delaware Ave.	EB	2	400	1600	1000	1600
13-17	Delaware Ave.	EB	2	400	1600	1000	1600
14-15	Delaware Ave.	EB	2	400	1600	1000	1600
14-17	Delaware Ave.	EB	2	400	1600	1000	1600
16-17	Pomeroy Trail	NB					
		SB					

Table A-A-2 Link Usage – Pedestrian (Pedestrians per hour)

Link	Street name	Dir	7pm-7am	7am-10am	10am-3pm	3pm-7pm
1-2	E. Cleveland St.	EB	0	100	50	100
		WB	0	100	50	100
1-4	N. College Ave.	NB	0	100	200	400
		SB	0	400	200	100
2-3	E. Cleveland St.	EB	0	50	25	50
		WB	0	50	25	50
2-7	N. Chapel St.	NB	0	25	50	50
		SB	0	50	25	50
2-16	Pomeroy Trail	NB	0	10	10	10
		SB	0	10	10	10
3-9	Capital Tr.	NB	0	10	10	10
		SB	0	10	10	10
4-5	E. Main St.	EB	0	100	200	200
		WB	0	100	200	200
4-10	S. College Ave.	NB	0	200	200	200
		SB	0	200	200	200
5-6	E. Main St.	EB	0	100	200	200
		WB	0	100	200	200
5-11	Academy St.	NB	0	100	200	200
		SB	0	100	200	200
6-7	E. Main St.	EB	0	100	200	200
		WB	0	100	200	200
6-12	Haines St.	NB	0	50	100	100
		SB	0	50	100	100
7-13	S. Chapel St.	NB	0	50	100	100
		SB	0	50	100	100
7-16	E. Main St.	EB	0	50	100	100
		WB	0	100	100	100
8-9	E. Main St.	EB	0	50	100	100
		WB	0	100	100	100
8-14	Tyre Ave.	NB	0	10	10	10
		SB	0	10	10	10
8-16	E. Main St.	EB	0	50	100	100
		WB	0	100	100	100
9-15	Library Ave.	NB	0	10	10	10
		SB	0	10	10	10
10-11	Delaware Ave.	EB	0	100	200	200
		WB	0	200	200	100
11-12	Delaware Ave.	EB	0	100	200	200
		WB	0	200	200	100
12-13	Delaware Ave.	EB	0	100	200	200
		WB	0	200	200	100
13-17	Delaware Ave.	EB	0	100	200	200
		WB	0	200	200	100
14-15	Delaware Ave.	EB	0	100	200	200
		WB	0	200	200	100

14-17	Delaware Ave.	EB	0	100	200	200
		WB	0	200	200	100
16-17	Pomeroy Trail	NB	0	10	10	10
		SB	0	10	10	10

Table A-A-3 Link Usage – Bicycle (bicycles per hour per direction)

Link	Street name	Dir	7pm-7am	7am-10am	10am-3pm	3pm-7pm
1-2	E. Cleveland St.	EB	0	10	5	10
		WB	0	10	5	10
1-4	N. College Ave.	NB	0	5	5	10
		SB	0	10	5	5
2-3	E. Cleveland St.	EB	0	10	5	10
		WB	0	10	5	10
2-7	N. Chapel St.	NB	0	5	5	5
		SB	0	5	5	5
2-16	Pomeroy Trail	NB	0	10	10	10
		SB	0	10	10	10
3-9	Capital Tr.	NB	0	5	5	5
		SB	0	5	5	5
4-5	E. Main St.	WB	0	10	10	10
4-10	S. College Ave.	NB	0	10	10	10
		SB	0	10	10	10
5-6	E. Main St.	WB	0	10	10	10
5-11	Academy St.	NB	0	10	10	10
		SB	0	10	10	10
6-7	E. Main St.	WB	0	10	10	10
6-12	Haines St.	NB	0	5	5	5
		SB	0	5	5	5
7-13	S. Chapel St.	NB	0	5	5	5
		SB	0	5	5	5
7-16	E. Main St.	WB	0	10	10	10
8-9	E. Main St.	WB	0	10	10	10
8-14	Tyre Ave.	NB	0	5	5	5
		SB	0	5	5	5
8-16	E. Main St.	WB	0	10	10	10
9-15	Library Ave.	NB	0	5	5	5
		SB	0	5	5	5
10-11	Delaware Ave.	EB	0	10	10	10
11-12	Delaware Ave.	EB	0	10	10	10
12-13	Delaware Ave.	EB	0	10	10	10
13-17	Delaware Ave.	EB	0	10	10	10
14-15	Delaware Ave.	EB	0	10	10	10
14-17	Delaware Ave.	EB	0	10	10	10
16-17	Pomeroy Trail	NB	0	10	10	10
		SB	0	10	10	10

Table A-A-4 Peak hour O-D Demand of Vehicles, Bicycles and Pedestrians

O-D Summary		Automobile/hr Demand	Bicycles/hr	Pedestrian/hr
Origin Node	Destination Node	Auto Demand	Bike Demand	Ped Demand
1	1	0	0	0
1	2	300	4	4
1	3	300	4	4
1	4	300	4	4
1	5	100	2	2
1	6	40	1	1
1	7	40	1	1
1	8	40	1	1
1	9	100	2	2
1	10	100	2	2
1	11	40	1	1
1	12	40	1	1
1	13	100	2	2
1	14	40	1	1
1	15	100	2	2
1	16	0	0	0
1	17	0	0	0
2	1	100	2	2
2	2	0	0	0
2	3	500	5	5
2	4	300	6	6
2	5	40	1	1
2	6	40	1	1
2	7	200	4	4
2	8	40	1	1
2	9	200	4	4
2	10	100	2	2
2	11	40	1	1
2	12	40	1	1
2	13	400	5	5
2	14	40	1	1
2	15	200	4	4
2	16	0	5	0
2	17	0	8	0
3	1	300	6	6
3	2	500	5	5
3	3	0	0	0
3	4	100	2	2
3	5	40	1	1

O-D Summary		Automobile/hr	Bicycles/hr	Pedestrian/hr
		Demand		
Origin Node	Destination Node	Auto Demand	Bike Demand	Ped Demand
3	6	40	1	1
3	7	40	1	1
3	8	40	1	1
3	9	200	4	4
3	10	100	2	2
3	11	40	1	1
3	12	40	1	1
3	13	100	2	2
3	14	40	1	1
3	15	200	4	4
3	16	0	0	0
3	17	0	0	0
4	1	100	2	2
4	2	100	2	2
4	3	100	2	2
4	4	0	0	0
4	5	40	1	1
4	6	40	1	1
4	7	40	1	1
4	8	40	1	1
4	9	100	2	2
4	10	100	2	2
4	11	40	1	1
4	12	40	1	1
4	13	100	2	2
4	14	40	1	1
4	15	100	2	2
4	16	0	0	0
4	17	0	0	0
5	1	40	1	1
5	2	40	1	1
5	3	40	1	1
5	4	40	1	1
5	5	0	0	0
5	6	25	1	1
5	7	25	1	1
5	8	25	1	1
5	9	40	1	1
5	10	40	1	1
5	11	25	1	1
5	12	25	1	1

O-D Summary		Automobile/hr	Bicycles/hr	Pedestrian/hr
		Demand		
Origin Node	Destination Node	Auto Demand	Bike Demand	Ped Demand
5	13	40	1	1
5	14	25	1	1
5	15	40	1	1
5	16	0	0	0
5	17	0	0	0
6	1	40	1	1
6	2	40	1	1
6	3	40	1	1
6	4	40	1	1
6	5	25	1	1
6	6	0	0	0
6	7	25	1	1
6	8	25	1	1
6	9	40	1	1
6	10	40	1	1
6	11	25	1	1
6	12	25	1	1
6	13	40	1	1
6	14	25	1	1
6	15	40	1	1
6	16	0	0	0
6	17	0	0	0
7	1	40	1	1
7	2	40	1	1
7	3	40	1	1
7	4	40	1	1
7	5	25	1	1
7	6	25	1	1
7	7	0	0	0
7	8	25	1	1
7	9	40	1	1
7	10	40	1	1
7	11	25	1	1
7	12	25	1	1
7	13	40	1	1
7	14	25	1	1
7	15	40	1	1
7	16	0	0	0
7	17	0	0	0
8	1	40	1	1
8	2	40	1	1

O-D Summary		Automobile/hr	Bicycles/hr	Pedestrian/hr
		Demand		
Origin Node	Destination Node	Auto Demand	Bike Demand	Ped Demand
8	3	40	1	1
8	4	40	1	1
8	5	25	1	1
8	6	25	1	1
8	7	25	1	1
8	8	0	0	0
8	9	40	1	1
8	10	40	1	1
8	11	25	1	1
8	12	25	1	1
8	13	40	1	1
8	14	25	1	1
8	15	40	1	1
8	16	0	0	0
8	17	0	0	0
9	1	100	2	2
9	2	200	4	4
9	3	300	6	6
9	4	200	4	4
9	5	40	1	1
9	6	40	1	1
9	7	40	1	1
9	8	40	1	1
9	9	0	0	0
9	10	100	2	2
9	11	40	1	1
9	12	40	1	1
9	13	100	2	2
9	14	40	1	1
9	15	500	6	6
9	16	0	0	0
9	17	0	0	0
10	1	300	6	6
10	2	100	2	2
10	3	100	2	2
10	4	100	2	2
10	5	100	2	2
10	6	40	1	1
10	7	40	1	1
10	8	40	1	1
10	9	100	2	2

O-D Summary		Automobile/hr	Bicycles/hr	Pedestrian/hr
		Demand		
Origin Node	Destination Node	Auto Demand	Bike Demand	Ped Demand
10	10	0	0	0
10	11	40	1	1
10	12	40	1	1
10	13	100	2	2
10	14	40	1	1
10	15	100	2	2
10	16	0	0	0
10	17	0	0	0
11	1	40	1	1
11	2	40	1	1
11	3	40	1	1
11	4	40	1	1
11	5	200	4	4
11	6	25	1	1
11	7	25	1	1
11	8	25	1	1
11	9	40	1	1
11	10	40	1	1
11	11	0	0	0
11	12	25	1	1
11	13	40	1	1
11	14	25	1	1
11	15	40	1	1
11	16	0	0	0
11	17	0	0	0
12	1	40	1	1
12	2	40	1	1
12	3	40	1	1
12	4	40	1	1
12	5	25	1	1
12	6	25	1	1
12	7	25	1	1
12	8	25	1	1
12	9	40	1	1
12	10	40	1	1
12	11	25	1	1
12	12	0	0	0
12	13	40	1	1
12	14	25	1	1
12	15	40	1	1
12	16	0	0	0

O-D Summary		Automobile/hr	Bicycles/hr	Pedestrian/hr
		Demand		
Origin Node	Destination Node	Auto Demand	Bike Demand	Ped Demand
12	17	0	0	0
13	1	100	2	2
13	2	400	4	4
13	3	100	2	2
13	4	100	2	2
13	5	40	1	1
13	6	40	1	1
13	7	200	4	4
13	8	40	1	1
13	9	100	2	2
13	10	100	2	2
13	11	40	1	1
13	12	40	1	1
13	13	0	0	0
13	14	40	1	1
13	15	100	2	2
13	16	0	0	0
13	17	0	0	0
14	1	40	1	1
14	2	40	1	1
14	3	40	1	1
14	4	40	1	1
14	5	25	1	1
14	6	25	1	1
14	7	25	1	1
14	8	25	1	1
14	9	40	1	1
14	10	40	1	1
14	11	25	1	1
14	12	25	1	1
14	13	40	1	1
14	14	0	0	0
14	15	40	1	1
14	16	0	0	0
14	17	0	0	0
15	1	100	2	2
15	2	100	2	2
15	3	100	2	2
15	4	100	2	2
15	5	40	1	1
15	6	40	1	1

O-D Summary		Automobile/hr	Bicycles/hr	Pedestrian/hr
		Demand		
Origin Node	Destination Node	Auto Demand	Bike Demand	Ped Demand
15	7	40	1	1
15	8	40	1	1
15	9	100	2	2
15	10	100	2	2
15	11	40	1	1
15	12	40	1	1
15	13	100	2	2
15	14	40	1	1
15	15	0	0	0
15	16	0	0	0
15	17	0	0	0
16	1	0	1	1
16	2	0	4	1
16	3	0	1	1
16	4	0	1	1
16	5	0	1	1
16	6	0	1	1
16	7	0	1	1
16	8	0	1	1
16	9	0	1	1
16	10	0	1	1
16	11	0	1	1
16	12	0	1	1
16	13	0	1	1
16	14	0	1	1
16	15	0	1	1
16	16	0	0	0
16	17	0	1	1
17	1	0	1	1
17	2	0	5	1
17	3	0	1	1
17	4	0	1	1
17	5	0	1	1
17	6	0	1	1
17	7	0	1	1
17	8	0	1	1
17	9	0	1	1
17	10	0	1	1
17	11	0	1	1
17	12	0	1	1
17	13	0	1	1

O-D Summary		Automobile/hr	Bicycles/hr	Pedestrian/hr
		Demand		
Origin Node	Destination Node	Auto Demand	Bike Demand	Ped Demand
17	14	0	1	1
17	15	0	1	1
17	16	0	1	1
17	17	0	0	0

APPENDIX B

Pavement Condition Data for Example Network

Pavement condition data was obtained from Delaware Department of Transportation (DelDOT). DelDOT used the Overall Pavement Index (OPT) for state roads and the Pavement Condition Index for local roads. OPT is a deduct-value composite index of pavement distresses based on weighted ratings of distress extent and severity, which is then subtracted from an initial score of 100. Pavement data for the state roads are shown in Table B-1. Pavement data for the local roads (City of Newark) are shown in Table B-2.

Table B-1 Pavement Condition Data for DelDOT Roads

Route	Direction	Begin Mile	End Mile	Length	Lane Miles	OPC Index	Pavement Type	Work Code	Last Treatment	Last Treatment Year	Last Year Rehab Year
SR273 - DELAWARE AVENUE	N/E	2.44	3.21	0.77	0.77	87.4	Composite	Composite Mill & Overlay	Comp. Mill & Overlay	2006	2006
SR273 - DELAWARE AVENUE	N/E	3.21	3.74	0.53	0.53	60.9	Composite	Composite Mill & Overlay	Comp. Mill & Overlay	2006	2006
SR2 SR72 - CAPITOL TRAIL	N/E	3.74	4.82	1.08	2.16	72.5	Composite	Composite Mill & Overlay	Comp. Mill & Overlay	2004	2004
SR2 SR72 - CAPITOL TRAIL	S/W	24.79	25.94	1.15	2.30	79.5	Composite	Composite (New)		1995	1995
SR273 -E. MAIN STREET	S/W	25.94	27.01	1.07	2.14	73.4	Composite	Composite (New)		1992	1992
NORTH CHAPEL STREET	All	0.00	0.43	0.43	0.86	67.9	Composite	Composite Mill & Overlay	Comp. Mill & Overlay	2003	2003
E. CLEVELAND AVE.	All	0.00	1.30	1.30	2.60	68.4	Asphalt	Composite Mill & Overlay	Comp. Mill & Overlay	2004	2004
NORTH COLLEGE AVENUE	All	0.00	0.51	0.51	1.02	42.4	Asphalt	AC Patching	Patch - BIT - 5%	2010	1994
S. CHAPEL STREET	All	0.00	0.72	0.72	1.44	78.2	Asphalt	AC Patching	Patch - BIT - 5%	2010	1989
S. COLLEGE AVENUE	All	8.10	8.87	0.77	1.54	87.0	Composite	Mill and Overlay	Mill and Overlay	2007	2007

Table B-2 Pavement Condition Data for City of Newark Streets

Street Name	From Street	To Street	Age Initial	Age	PCI	Year	Treatment
ACADEMY ST-1	E. MAIN ST	DELAWARE AVE	20	20	47.17	2016	Rehab-Functional
HAINES ST-4	DELAWARE AVE.	EAST MAIN STREET	24	24	32.73	2016	Rehab-Structural
TYRE AVENUE-1	DELAWARE AVENUE	DELAWARE CIRCLE	4	2	96.63	2016	Monitor
TYRE AVENUE-2	DELAWARE CIRCLE	EAST MAIN STREET	4	2	96.63	2016	Monitor

APPENDIX C

Detail Input Data for Modeling the Enhanced Network

This appendix shows the shows the source of the data to develop the enhanced network described in Chapter 5.

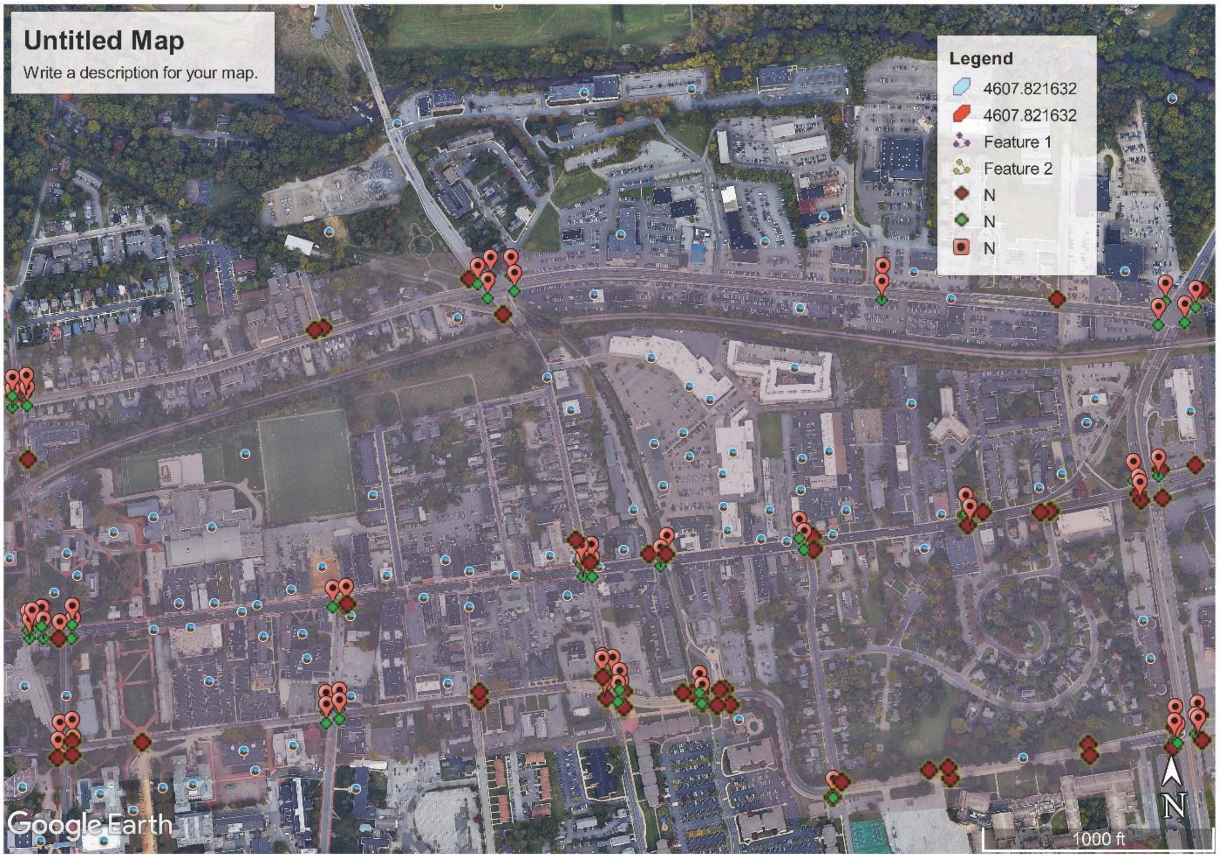

Figure C-1 Overlay of Intersections on GoogleEarth Data

Figure C-2 Parking Lot and On Street Parking Spots Distribution in the Research Area

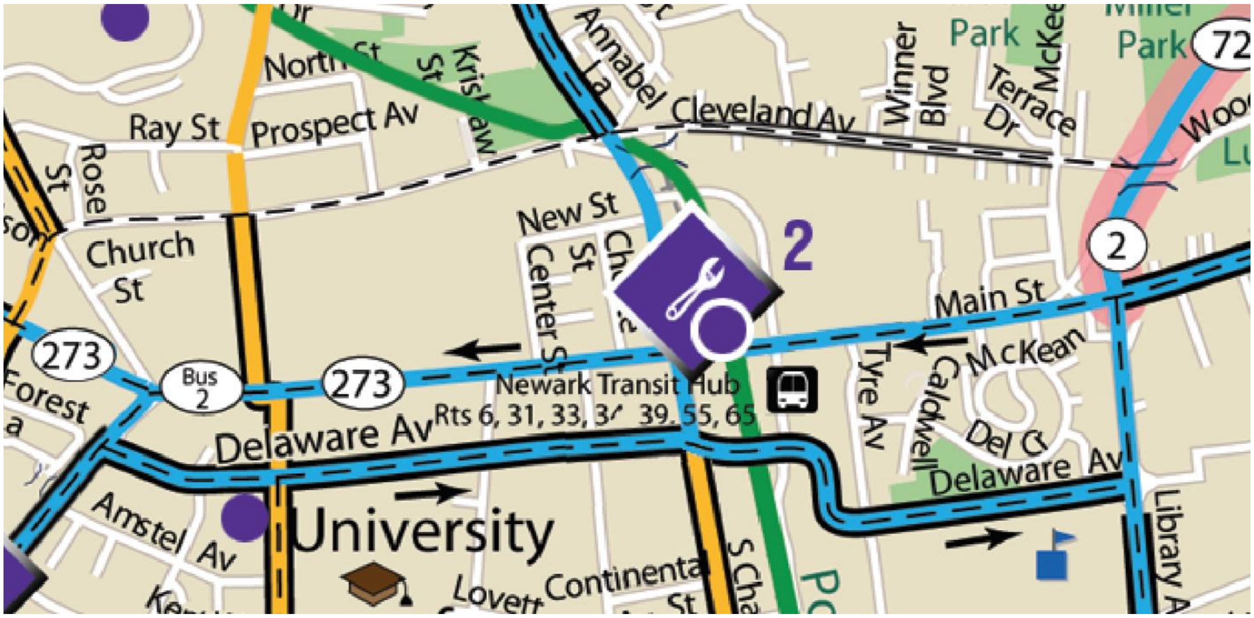

Figure C-3 Bike Lanes (blue) in the Research Area

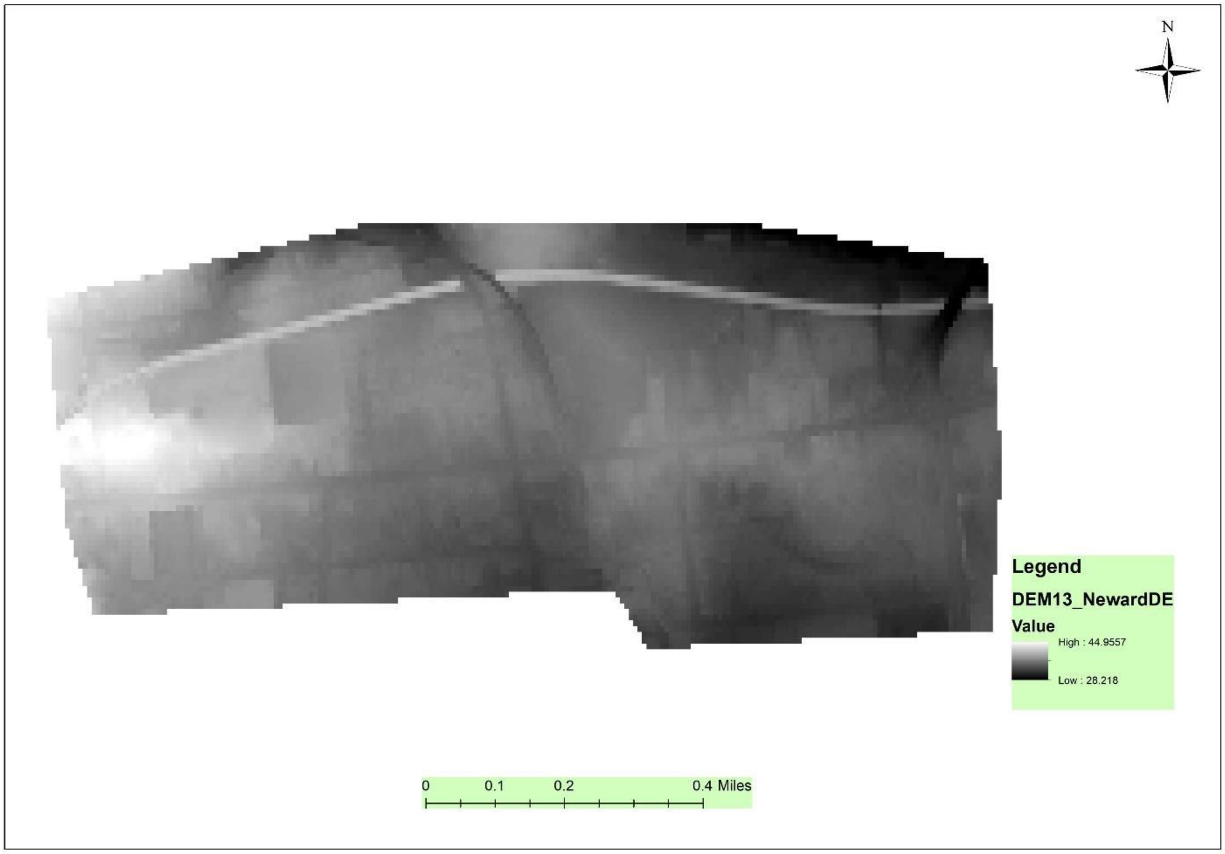

Figure C-4 DEM of Research Area (1 meter resolution)

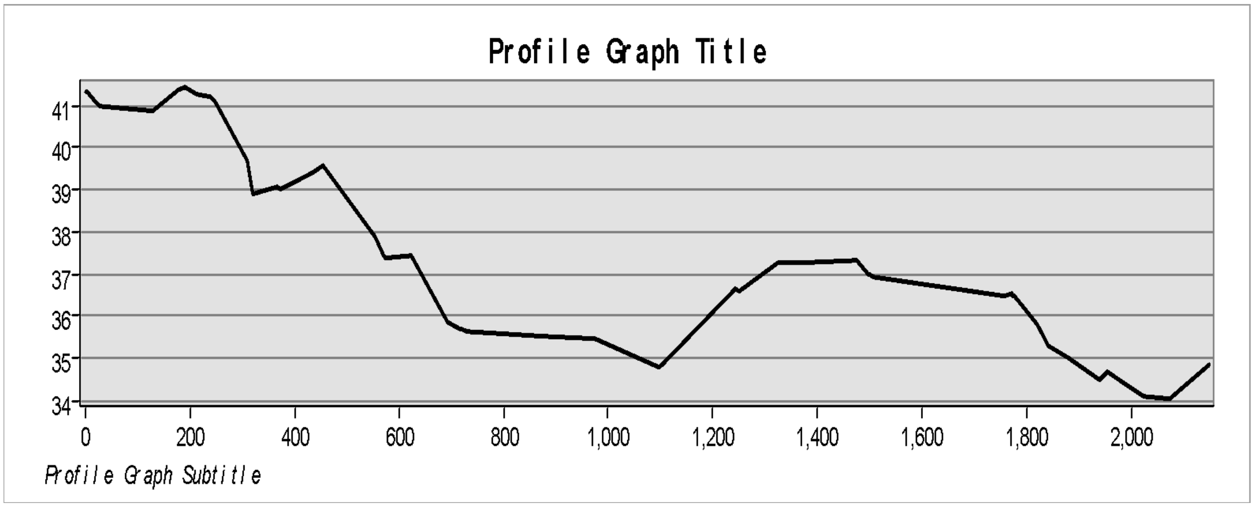

Figure C-5 An Example of Elevation Profile of E. Main Street

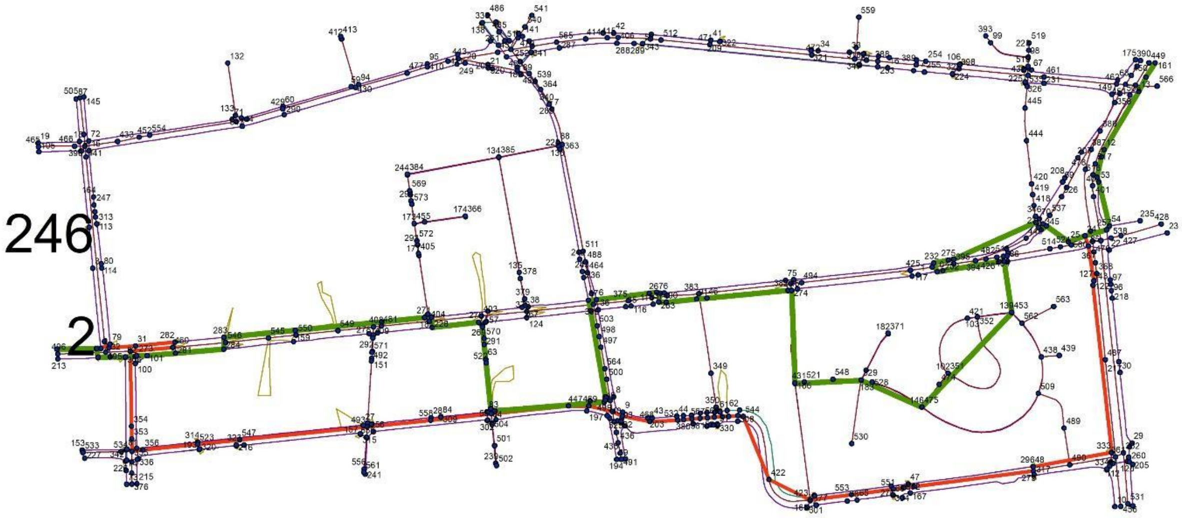

Figure C-6 An Example of VSP from Node 185 to Node 161 for Minimum Free Travel Time (Red)

APPENDIX D

Project Attribute for Example Network

Project attributes for the example network are shown in Table D-1.

Table D-1 Summary of Estimated Construction Cost, Construction Duration, Action Code, and Index for Each Project

Action Category Code	Action Category	Project Index	Street Name	O	D	Mode	Duration (days)	Cost (USD)
1	Reconstruction 1	0	N. College Ave	1	4	Vehicle	2	148250
1	Reconstruction 1	1	N. College Ave	4	1	Vehicle	2	148250
1	Reconstruction 1	2	Academy St.	5	11	Vehicle	2	114557
1	Reconstruction 1	3	Academy St.	11	5	Vehicle	2	114557
1	Reconstruction 1	4	Haines St.	6	12	Vehicle	2	101079
1	Reconstruction 1	5	Haines St.	12	6	Vehicle	2	101079
1	Reconstruction 1	6	Capital Tr.	3	9	Vehicle	6	510715
1	Reconstruction 1	7	Capital Tr.	9	3	Vehicle	6	510715
2	Major repair	8	Library Ave.	9	15	Vehicle	2	152064
2	Major repair	9	Library Ave.	15	9	Vehicle	2	152064
2	Major repair	10	E. Main St. (WB)	5	4	Vehicle	2	139392
2	Major repair	11	E. Main St. (WB)	6	5	Vehicle	1	76032
2	Major repair	12	E. Main St. (WB)	7	6	Vehicle	1	76032
2	Major repair	13	E. Main St. (WB)	16	7	Vehicle	1	76032
2	Major repair	14	E. Main St. (WB)	8	16	Vehicle	1	76032
2	Major repair	15	E. Main St. (WB)	18	8	Vehicle	2	152064
2	Major repair	16	E. Main St. (WB)	9	18	Vehicle	1	76032
2	Major repair	17	Delaware Ave. (EB)	10	11	Vehicle	2	152064
2	Major repair	18	Delaware Ave. (EB)	11	12	Vehicle	1	76032
2	Major repair	19	Delaware Ave. (EB)	12	13	Vehicle	1	76032
2	Major repair	20	Delaware Ave. (EB)	13	17	Vehicle	1	76032
2	Major repair	21	Delaware Ave. (EB)	17	14	Vehicle	2	114048
2	Major repair	22	Delaware Ave. (EB)	14	19	Vehicle	3	228096
2	Major repair	23	Delaware Ave. (EB)	19	15	Vehicle	1	38016
3	Minor repair	24	E. Cleveland St.	1	2	Vehicle	1	33635
3	Minor repair	25	E. Cleveland St.	2	1	Vehicle	1	33635
3	Minor repair	26	E. Cleveland St.	2	3	Vehicle	1	50453
3	Minor repair	27	E. Cleveland St.	3	2	Vehicle	1	50453
3	Minor repair	28	N. College Ave.	1	4	Vehicle	1	15977
3	Minor repair	29	N. College Ave.	4	1	Vehicle	1	15977
3	Minor repair	30	S. College Ave.	4	10	Vehicle	1	10091

3	Minor repair	31	S. College Ave.	10	4	Vehicle	1	10091
3	Minor repair	32	N. Chapel St.	2	7	Vehicle	1	25227
3	Minor repair	33	N. Chapel St.	7	2	Vehicle	1	25227
3	Minor repair	34	S. Chapel St.	7	13	Vehicle	1	8409
3	Minor repair	35	S. Chapel St.	13	7	Vehicle	1	8409
4	Reconstruction 2	36	E. Cleveland St.	1	2	Walking	5	84128
4	Reconstruction 2	37	E. Cleveland St.	2	1	Walking	5	84128
4	Reconstruction 2	38	N. College Ave.	1	4	Walking	3	39961
4	Reconstruction 2	39	N. College Ave.	4	1	Walking	3	39961
4	Reconstruction 2	40	E. Cleveland St.	2	3	Walking	8	126192
4	Reconstruction 2	41	E. Cleveland St.	3	2	Walking	8	126192
4	Reconstruction 2	42	Capital Tr.	3	9	Walking	3	42064
4	Reconstruction 2	43	Capital Tr.	9	3	Walking	3	42064
4	Reconstruction 2	44	Library Ave.	9	15	Walking	3	42064
4	Reconstruction 2	45	Library Ave.	15	9	Walking	3	42064
5	Reconstruction 3	46	E. Cleveland St.	2	3	Bike	1	37664
5	Reconstruction 3	47	E. Cleveland St.	3	2	Bike	1	37664
5	Reconstruction 3	48	S. College Ave.	4	10	Bike	1	18832
5	Reconstruction 3	49	S. College Ave.	10	4	Bike	1	18832

APPENDIX E

Risk Scores for Arcs in the Example Network

Risk scores for arcs in the bicycle and pedestrian network are shown in Table E-1 and Table E-2.

Table E-1 Risk Scores for Bike Arcs

No.	I	J	RAW_RISK	RISK_SCORE	No.	I	J	RAW_RISK	RISK_SCORE
0	324	305	10	0	55	342	307	10	0
1	305	324	10	0	56	307	342	10	0
2	250	327	0	0	57	334	333	10	0
3	250	316	10	0	58	333	334	10	0
4	316	250	10	0	59	343	332	0	0
5	318	321	0	0	60	343	328	34	1
6	300	301	0	0	61	328	343	34	1
7	315	302	0	0	62	142	344	34	1
8	302	308	50	1	63	344	142	34	1
9	308	302	50	1	64	612	305	0	0
10	301	304	0	0	65	612	315	0	0
11	305	313	0	0	66	315	612	0	0
12	306	307	0	0	67	613	612	0	0
13	310	311	0	0	68	601	613	0	0
14	311	325	34	1	69	611	601	34	1
15	325	311	34	1	70	614	611	0	0
16	311	318	0	0	71	610	614	0	0
17	323	315	0	0	72	607	610	0	0
18	313	316	0	0	73	606	607	10	0
19	304	317	0	0	74	605	606	0	0
20	317	334	0	0	75	606	310	0	0
21	318	332	10	0	76	326	607	0	0
22	332	318	10	0	77	340	601	0	0
23	319	324	10	0	78	601	340	0	0
24	324	319	10	0	79	601	615	10	0
25	319	306	0	0	80	615	601	10	0
26	336	320	0	0	81	615	331	0	0
27	320	323	0	0	82	331	615	0	0
28	302	40	0	0	83	328	142	0	0

29	321	322	0	0	84	341	343	0	0
30	322	328	0	0	85	604	341	10	0
31	325	326	0	0	86	341	604	10	0
32	326	310	34	1	87	316	616	0	0
33	310	326	34	1	88	616	604	34	1
34	327	324	0	0	89	251	603	0	0
35	332	325	0	0	90	603	602	34	1
36	330	300	0	0	91	602	603	34	1
37	40	312	10	0	92	602	250	34	1
38	312	40	10	0	93	250	602	34	1
39	331	335	0	0	94	316	603	50	1
40	335	40	10	0	95	603	316	50	1
41	40	335	10	0	96	251	604	34	1
42	312	330	0	0	97	604	251	34	1
43	336	192	0	0	98	608	610	0	0
44	192	336	0	0	99	609	333	0	0
45	336	342	46	1	100	333	609	0	0
46	342	336	46	1	101	608	609	34	1
47	338	251	0	0	102	609	608	34	1
48	338	339	34	1	103	607	608	0	0
49	339	338	34	1	104	608	607	0	0
50	344	339	0	0	105	613	308	0	0
51	344	251	0	0	106	308	613	0	0
52	251	344	0	0	107	614	301	0	0
53	340	341	0	0	108	301	614	0	0
54	341	142	10	0					

Table E-2 Risk Scores for Pedestrian Arcs

No.	I	J	RAW_RISK	RISK_SCORE	No.	I	J	RAW_RISK	RISK_SCORE
0	0	1	0	0	342	100	108	0	0
1	1	0	0	0	343	108	100	0	0
2	0	232	49	1	344	100	272	0	0
3	232	0	49	1	345	272	100	0	0
4	0	202	43	1	346	101	273	0	0
5	202	0	43	1	347	273	101	0	0
6	1	117	43	1	348	101	281	0	0
7	117	1	43	1	349	281	101	0	0
8	2	3	0	0	350	102	103	0	0
9	3	2	0	0	351	103	102	0	0
10	2	184	0	0	352	102	146	0	0
11	184	2	0	0	353	146	102	0	0
12	2	79	49	1	354	103	139	0	0
13	79	2	49	1	355	139	103	0	0
14	3	246	0	0	356	104	105	0	0
15	246	3	0	0	357	105	104	0	0
16	4	5	0	0	358	106	107	0	0
17	5	4	0	0	359	107	106	0	0
18	4	246	43	1	360	106	254	0	0
19	246	4	43	1	361	254	106	0	0
20	5	15	43	1	362	106	224	43	1
21	15	5	43	1	363	224	106	43	1
22	5	104	0	0	364	107	245	43	1
23	104	5	0	0	365	245	107	43	1
24	5	18	49	1	366	108	147	0	0
25	18	5	49	1	367	147	108	0	0
26	6	7	0	0	368	108	192	49	1
27	7	6	0	0	369	192	108	49	1
28	6	26	0	0	370	110	111	0	0
29	26	6	0	0	371	111	110	0	0
30	6	36	49	1	372	110	121	67	1
31	36	6	49	1	373	121	110	67	1
32	6	37	43	1	374	111	112	0	0
33	37	6	43	1	375	112	111	0	0
34	7	285	43	1	376	111	258	0	0
35	285	7	43	1	377	258	111	0	0
36	8	9	0	0	378	113	114	0	0
37	9	8	0	0	379	114	113	0	0
38	8	36	0	0	380	113	191	43	1
39	36	8	0	0	381	191	113	43	1
40	8	154	56	1	382	115	116	0	0

41	154	8	56	1	383	116	115	0	0
42	9	203	0	0	384	115	263	43	1
43	203	9	0	0	385	263	115	43	1
44	9	93	62	1	386	117	118	0	0
45	93	9	62	1	387	118	117	0	0
46	10	11	0	0	388	118	274	43	1
47	11	10	0	0	389	274	118	43	1
48	11	112	43	1	390	118	233	43	1
49	112	11	43	1	391	233	118	43	1
50	11	168	0	0	392	119	120	0	0
51	168	11	0	0	393	120	119	0	0
52	12	13	0	0	394	119	155	0	0
53	13	12	0	0	395	155	119	0	0
54	12	280	0	0	396	119	260	0	0
55	280	12	0	0	397	260	119	0	0
56	13	149	59	1	398	120	258	62	1
57	149	13	59	1	399	258	120	62	1
58	13	160	43	1	400	121	122	0	0
59	160	13	43	1	401	122	121	0	0
60	14	15	0	0	402	122	127	43	1
61	15	14	0	0	403	127	122	43	1
62	14	248	43	1	404	123	124	0	0
63	248	14	43	1	405	124	123	0	0
64	14	290	0	0	406	123	154	0	0
65	290	14	0	0	407	154	123	0	0
66	15	164	0	0	408	124	270	0	0
67	164	15	0	0	409	270	124	0	0
68	15	72	59	1	410	125	126	0	0
69	72	15	59	1	411	126	125	0	0
70	16	17	0	0	412	125	187	43	1
71	17	16	0	0	413	187	125	43	1
72	16	253	0	0	414	128	129	0	0
73	253	16	0	0	415	129	128	0	0
74	17	255	43	1	416	128	170	0	0
75	255	17	43	1	417	170	128	0	0
76	18	19	0	0	418	129	254	43	1
77	19	18	0	0	419	254	129	43	1
78	18	87	0	0	420	130	131	0	0
79	87	18	0	0	421	131	130	0	0
80	18	72	43	1	422	130	230	0	0
81	72	18	43	1	423	230	130	0	0
82	20	21	0	0	424	131	275	43	1
83	21	20	0	0	425	275	131	43	1

84	20	249	43	1
85	249	20	43	1
86	21	206	43	1
87	206	21	43	1
88	22	23	0	0
89	23	22	0	0
90	22	143	0	0
91	143	22	0	0
92	22	85	49	1
93	85	22	49	1
94	22	257	67	1
95	257	22	67	1
96	24	25	0	0
97	25	24	0	0
98	24	85	49	1
99	85	24	49	1
100	24	257	59	1
101	257	24	59	1
102	25	234	0	0
103	234	25	0	0
104	26	265	43	1
105	265	26	43	1
106	27	28	0	0
107	28	27	0	0
108	27	152	43	1
109	152	27	43	1
110	27	56	49	1
111	56	27	49	1
112	28	84	43	1
113	84	28	43	1
114	29	30	0	0
115	30	29	0	0
116	29	259	43	1
117	259	29	43	1
118	30	217	43	1
119	217	30	43	1
120	31	32	0	0
121	32	31	0	0
122	31	273	59	1
123	273	31	59	1
124	31	282	0	0
125	282	31	0	0
126	32	79	0	0
426	132	133	0	0
427	133	132	0	0
428	133	248	0	0
429	248	133	0	0
430	134	135	0	0
431	135	134	0	0
432	134	136	0	0
433	136	134	0	0
434	134	244	0	0
435	244	134	0	0
436	135	266	0	0
437	266	135	0	0
438	136	220	43	1
439	220	136	43	1
440	137	138	0	0
441	138	137	0	0
442	137	144	0	0
443	144	137	0	0
444	139	140	0	0
445	140	139	0	0
446	139	146	0	0
447	146	139	0	0
448	140	201	43	1
449	201	140	43	1
450	141	163	43	1
451	163	141	43	1
452	141	252	49	1
453	252	141	49	1
454	141	286	0	0
455	286	141	0	0
456	146	183	0	0
457	183	146	0	0
458	147	148	0	0
459	148	147	0	0
460	147	193	43	1
461	193	147	43	1
462	148	152	43	1
463	152	148	43	1
464	148	157	59	1
465	157	148	59	1
466	149	150	0	0
467	150	149	0	0
468	149	231	0	0

127	79	32	0	0	469	231	149	0	0
128	32	171	49	1	470	150	207	43	1
129	171	32	49	1	471	207	150	43	1
130	33	34	0	0	472	151	152	0	0
131	34	33	0	0	473	152	151	0	0
132	33	169	43	1	474	151	292	0	0
133	169	33	43	1	475	292	151	0	0
134	34	210	43	1	476	155	259	49	1
135	210	34	43	1	477	259	155	49	1
136	35	36	0	0	478	156	157	0	0
137	36	35	0	0	479	157	156	0	0
138	35	116	43	1	480	156	216	43	1
139	116	35	43	1	481	216	156	43	1
140	36	123	43	1	482	157	240	43	1
141	123	36	43	1	483	240	157	43	1
142	37	38	0	0	484	158	159	0	0
143	38	37	0	0	485	159	158	0	0
144	37	236	0	0	486	158	278	49	1
145	236	37	0	0	487	278	158	49	1
146	37	123	62	1	488	159	284	0	0
147	123	37	62	1	489	284	159	0	0
148	38	266	43	1	490	160	161	0	0
149	266	38	43	1	491	161	160	0	0
150	38	124	43	1	492	162	163	0	0
151	124	38	43	1	493	163	162	0	0
152	196	109	49	1	494	162	237	0	0
153	109	196	49	1	495	237	162	0	0
154	41	42	0	0	496	162	137	49	1
155	42	41	0	0	497	137	162	49	1
156	41	209	43	1	498	164	247	0	0
157	209	41	43	1	499	247	164	0	0
158	42	286	43	1	500	165	166	0	0
159	286	42	43	1	501	166	165	0	0
160	43	44	0	0	502	165	262	43	1
161	44	43	0	0	503	262	165	43	1
162	43	203	43	1	504	166	183	0	0
163	203	43	43	1	505	183	166	0	0
164	44	214	43	1	506	166	274	0	0
165	214	44	43	1	507	274	166	0	0
166	45	46	0	0	508	167	168	0	0
167	46	45	0	0	509	168	167	0	0
168	45	75	62	1	510	167	261	0	0
169	75	45	62	1	511	261	167	0	0

170	45	274	43	1
171	274	45	43	1
172	46	91	43	1
173	91	46	43	1
174	47	48	0	0
175	48	47	0	0
176	47	276	0	0
177	276	47	0	0
178	47	167	43	1
179	167	47	43	1
180	48	121	0	0
181	121	48	0	0
182	49	50	0	0
183	50	49	0	0
184	49	196	62	1
185	196	49	62	1
186	49	154	0	0
187	154	49	0	0
188	50	64	43	1
189	64	50	43	1
190	50	198	0	0
191	198	50	0	0
192	51	52	0	0
193	52	51	0	0
194	51	212	43	1
195	212	51	43	1
196	52	165	49	1
197	165	52	49	1
198	52	77	43	1
199	77	52	43	1
200	53	54	0	0
201	54	53	0	0
202	53	256	0	0
203	256	53	0	0
204	54	235	0	0
205	235	54	0	0
206	54	257	43	1
207	257	54	43	1
208	55	56	0	0
209	56	55	0	0
210	55	238	43	1
211	238	55	43	1
212	55	83	0	0
512	169	170	0	0
513	170	169	0	0
514	171	172	0	0
515	172	171	0	0
516	172	213	0	0
517	213	172	0	0
518	172	184	59	1
519	184	172	59	1
520	173	174	0	0
521	174	173	0	0
522	173	293	0	0
523	293	173	0	0
524	173	294	0	0
525	294	173	0	0
526	176	177	0	0
527	177	176	0	0
528	176	271	43	1
529	271	176	43	1
530	176	181	43	1
531	181	176	43	1
532	177	293	0	0
533	293	177	0	0
534	178	179	0	0
535	179	178	0	0
536	178	230	43	1
537	230	178	43	1
538	178	234	43	1
539	234	178	43	1
540	180	181	0	0
541	181	180	0	0
542	180	270	43	1
543	270	180	43	1
544	180	267	0	0
545	267	180	0	0
546	181	228	43	1
547	228	181	43	1
548	182	183	0	0
549	183	182	0	0
550	184	185	0	0
551	185	184	0	0
552	186	187	0	0
553	187	186	0	0
554	186	214	0	0

213	83	55	0	0	555	214	186	0	0
214	56	240	43	1	556	186	199	49	1
215	240	56	43	1	557	199	186	49	1
216	57	58	0	0	558	188	189	0	0
217	58	57	0	0	559	189	188	0	0
218	57	169	59	1	560	188	137	49	1
219	169	57	59	1	561	137	188	49	1
220	57	253	0	0	562	188	252	54	1
221	253	57	0	0	563	252	188	54	1
222	58	289	43	1	564	190	191	0	0
223	289	58	43	1	565	191	190	0	0
224	59	60	0	0	566	190	247	43	1
225	60	59	0	0	567	247	190	43	1
226	59	94	43	1	568	192	193	0	0
227	94	59	43	1	569	193	192	0	0
228	60	248	0	0	570	192	215	0	0
229	248	60	0	0	571	215	192	0	0
230	61	62	0	0	572	192	226	43	1
231	62	61	0	0	573	226	192	43	1
232	61	126	43	1	574	193	216	0	0
233	126	61	43	1	575	216	193	0	0
234	63	64	0	0	576	194	195	0	0
235	64	63	0	0	577	195	194	0	0
236	63	291	0	0	578	195	199	0	0
237	291	63	0	0	579	199	195	0	0
238	64	83	43	1	580	196	197	0	0
239	83	64	43	1	581	197	196	0	0
240	65	66	0	0	582	197	198	0	0
241	66	65	0	0	583	198	197	0	0
242	65	78	43	1	584	198	238	43	1
243	78	65	43	1	585	238	198	43	1
244	66	261	43	1	586	199	200	0	0
245	261	66	43	1	587	200	199	0	0
246	66	276	0	0	588	200	211	43	1
247	276	66	0	0	589	211	200	43	1
248	67	68	0	0	590	201	202	0	0
249	68	67	0	0	591	202	201	0	0
250	67	245	43	1	592	204	205	0	0
251	245	67	43	1	593	205	204	0	0
252	68	175	0	0	594	205	260	43	1
253	175	68	0	0	595	260	205	43	1
254	68	149	49	1	596	207	208	0	0
255	149	68	49	1	597	208	207	0	0

256	69	70	0	0
257	70	69	0	0
258	69	208	43	1
259	208	69	43	1
260	70	130	43	1
261	130	70	43	1
262	71	72	0	0
263	72	71	0	0
264	71	133	0	0
265	133	71	0	0
266	72	145	0	0
267	145	72	0	0
268	73	74	0	0
269	74	73	0	0
270	74	226	0	0
271	226	74	0	0
272	75	76	0	0
273	76	75	0	0
274	75	233	43	1
275	233	75	43	1
276	76	264	43	1
277	264	76	43	1
278	77	78	0	0
279	78	77	0	0
280	79	80	0	0
281	80	79	0	0
282	80	114	43	1
283	114	80	43	1
284	81	82	0	0
285	82	81	0	0
286	81	153	0	0
287	153	81	0	0
288	81	108	43	1
289	108	81	43	1
290	81	226	49	1
291	226	81	49	1
292	82	272	49	1
293	272	82	49	1
294	82	171	0	0
295	171	82	0	0
296	83	84	0	0
297	84	83	0	0
298	85	86	0	0
598	209	210	0	0
599	210	209	0	0
600	211	212	0	0
601	212	211	0	0
602	217	218	0	0
603	218	217	0	0
604	219	220	0	0
605	220	219	0	0
606	219	242	43	1
607	242	219	43	1
608	221	222	0	0
609	222	221	0	0
610	221	229	43	1
611	229	221	43	1
612	221	271	0	0
613	271	221	0	0
614	222	283	0	0
615	283	222	0	0
616	224	225	0	0
617	225	224	0	0
618	224	255	0	0
619	255	224	0	0
620	225	231	43	1
621	231	225	43	1
622	226	227	0	0
623	227	226	0	0
624	228	229	0	0
625	229	228	0	0
626	228	268	0	0
627	268	228	0	0
628	229	278	49	1
629	278	229	49	1
630	232	233	0	0
631	233	232	0	0
632	232	275	0	0
633	275	232	0	0
634	236	243	43	1
635	243	236	43	1
636	238	239	0	0
637	239	238	0	0
638	240	241	0	0
639	241	240	0	0
640	242	243	0	0

299	86	85	0	0	641	243	242	0	0
300	85	127	0	0	642	244	277	0	0
301	127	85	0	0	643	277	244	0	0
302	86	140	43	1	644	249	290	0	0
303	140	86	43	1	645	290	249	0	0
304	86	179	43	1	646	252	285	0	0
305	179	86	43	1	647	285	252	0	0
306	88	89	0	0	648	252	287	0	0
307	89	88	0	0	649	287	252	0	0
308	88	136	43	1	650	256	280	0	0
309	136	88	43	1	651	280	256	0	0
310	89	206	0	0	652	262	276	0	0
311	206	89	0	0	653	276	262	0	0
312	89	189	43	1	654	263	264	62	1
313	189	89	43	1	655	264	263	62	1
314	90	91	0	0	656	264	265	0	0
315	91	90	0	0	657	265	264	0	0
316	90	263	43	1	658	266	267	43	1
317	263	90	43	1	659	267	266	43	1
318	92	93	0	0	660	268	269	43	1
319	93	92	0	0	661	269	268	43	1
320	92	109	0	0	662	269	270	43	1
321	109	92	0	0	663	270	269	43	1
322	92	195	43	1	664	269	291	0	0
323	195	92	43	1	665	291	269	0	0
324	94	95	0	0	666	272	273	0	0
325	95	94	0	0	667	273	272	0	0
326	95	144	43	1	668	277	294	0	0
327	144	95	43	1	669	294	277	0	0
328	96	97	0	0	670	278	292	0	0
329	97	96	0	0	671	292	278	0	0
330	96	218	43	1	672	281	282	43	1
331	218	96	43	1	673	282	281	43	1
332	97	143	43	1	674	281	284	0	0
333	143	97	43	1	675	284	281	0	0
334	98	99	0	0	676	282	283	0	0
335	99	98	0	0	677	283	282	0	0
336	98	223	0	0	678	283	284	43	1
337	223	98	0	0	679	284	283	43	1
338	98	245	0	0	680	287	288	0	0
339	245	98	0	0	681	288	287	0	0
340	100	101	0	0	682	288	289	0	0
341	101	100	0	0	683	289	288	0	0