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Integrated stochastic economics performance evaluation of horizontal infrastructure systems

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Integrated stochastic economics performance evaluation of horizontal infrastructure systems

by

Ali Nahvi

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The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this dissertation. The Graduate College will ensure this dissertation is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University

Ames, Iowa

2019

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ABSTRACT

Many aspects of the nation’s infrastructure are in dire need of improvement, as effectively illustrated by the American Society of Civil Engineers (ASCE) and its Infrastructure Report Card. As of 2017, the ASCE gave American infrastructure a cumulative grade of D+ (“poor”), unchanged from the previous report card published in 2013. In its reports on individual categories of infrastructure, the ASCE has expanded on problems that have contributed to this poor grade. For example, they gave a D grade in the category of Roads, citing such problems as “traffic delays costing the country $160 billion in wasted time and fuel in 2014” and “one out of every five miles of highway pavement is in poor condition”. A D grade was also given to the nation’s aviation sector, because aviation infrastructure (including airports and traffic control systems) was deemed to be lagging far behind advancements in aircraft technology, leading to increased congestion and a projected “$42 billion funding gap between 2016 and 2025”.

Decision-making techniques are useful tools for overcoming economic issues in engineering projects; the choice of a suitable decision-making technique is in itself a critical decision because different techniques may yield different solutions. It is imperative for a decision maker to be aware of the underlying principles of a technique as well as its associated pitfalls. In other words, the proper application of civil engineering economic analysis demands particularly great expertise. The development of economic analysis tools that are widely applicable to a variety of engineering projects is also a broadly important endeavor for use in the civil engineering field.

CHAPTER 1. INTRODUCTION

Background

Public infrastructure is an essential part of the U.S. economy. Well-designed infrastructure investments can raise economic growth, productivity, and land values, while also providing significant positive spillovers to areas such as economic development, energy efficiency, public health and manufacturing. Investing rationally in infrastructure is critically important. Adapting economic analysis theory to develop decision-making platforms can help decision makers for making the best investment decision for building new or marinating existing infrastructure.

This dissertation documents how economic analysis theory has been adapted to developed decision making tools to evaluate the opportunities and challenges associated with the implementation of heated pavements systems and maintenance of low volume roads.

The aforementioned adaptations furnish agencies with approaches that increase the probability that the preferred alternative will produce the lowest life cycle cost and increased benefits. Therefore, the recommendations from this dissertation will not only be founded in economic analysis theory but will also provide various public transportation agencies with an added level of confidence in predicting the economic result of maintenance and technology alternatives of interest.

Heated pavement systems

Several recently-developed technologies for overcoming winter-related delays have been studied, including super-hydrophobic coating techniques (Arabzadeh, et al., 2016), phase-change materials (Farnam, et al., 2015), hydronically-heated pavement systems (HHPS) (Thurston, et al., 1985), and electrically-heated pavement systems (EHPS) (Abdualla, et al., 2016). Such technologies are intended to both decrease environmental effects of de-icers and reduce flight delays, with the ultimate goal of saving time, energy, and money.

"Hydronic heated pavement surfaces may be implemented by circulating heated fluid through a series of pipes running beneath the pavement" (Liu, et al., 2007) (Figure 1-1). Boilers fueled by natural gas or geothermal energy are typically used to supply warm water for such systems.

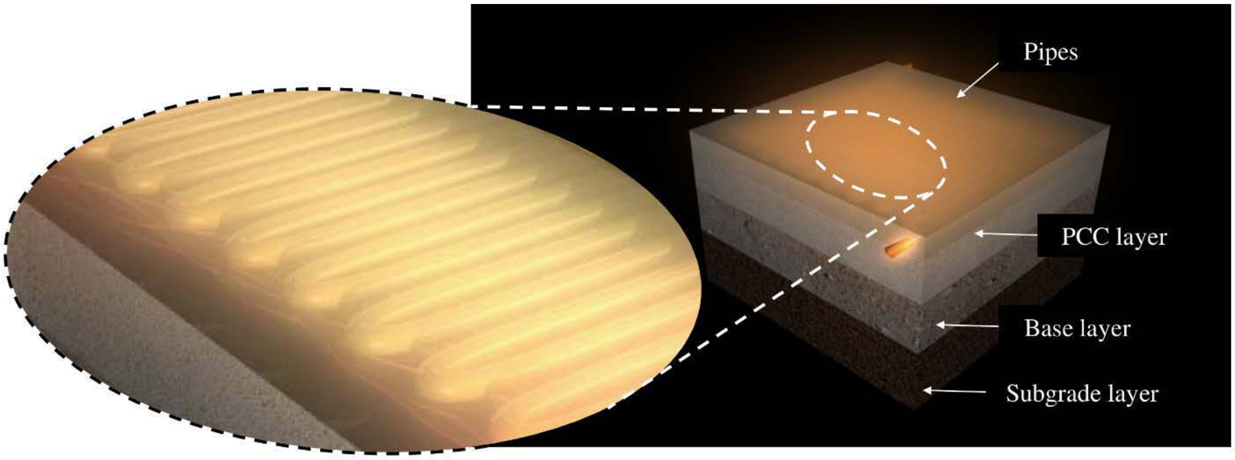
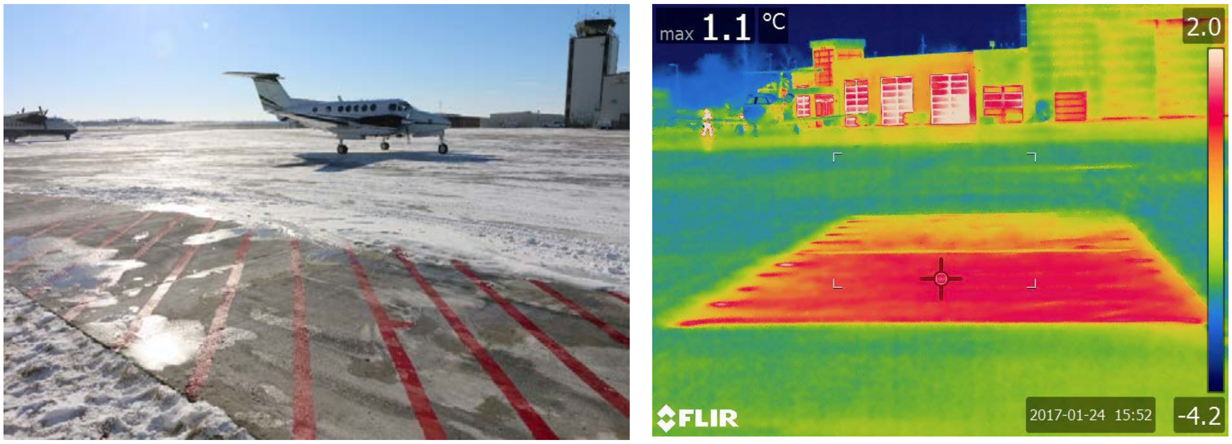


Figure 1-1 Details of a hydronically-heated pavement system (HHPS)
Created by Ali Arabzadeh

Application of HHPS for ice and snow removal operations has been reported as being effective and successful in European transportation infrastructure systems; in the U.S., while heated pavement was implemented for the first time on a bridge deck in Oregon (Thurston, et al., 1985), and since that time HHPS have been used in some countries (Pan, et al., 2015), before HHPS would be considered for airport implementation, it would be necessary to evaluate the prospective energy and cost effects of such systems, and the literature in this area does not reflect significant research attention to date given to these aspects (Pan, et al., 2015).

Electrically-conductive concrete-heated pavement systems (ECON HPS) are one type of EHPS, in which an electric potential is applied to pavement fabricated with electrically-conductive materials. Previously-studied conductive materials to be added to concrete include steel shavings (Tuan 2008), carbon powder (Farnam, et al., 2015), and carbon fibers (Sassani et al. 2018). In November 2016, the first full-scale ECON HPS test slabs made using electrically-conductive carbon fibers were built at a U.S. airport in the general-aviation apron at the Des Moines International Airport (DSM) in Iowa (Figure 1-2). Many activities occur on airport aprons (e.g., oil-refueling operations, baggage handling, etc.), the presence of machinery- and personnel-based activities also can impact the ability of effectively using more traditional snow and ice-removal operations in these locations (Merkert and Mangia 2012), so apron areas are strong candidates for the use of ECON HPS.



(a) **(b)**

Figure 1-2 Electrically-conductive concrete heated-pavement system (ECON HPS) full scale demonstration at Des Moines International Airport; a) ECON HPS snow melting (photo taken January 2016); b) Thermal camera view (photo taken February 2017)

Low-volume roads

This section provides background on Iowa low -volume roads and related feasibility studies and also provides a brief overview of Otta seal and economic evaluation of this surface-treatment technique.

The quality of materials in granular roadways (e.g., abrasion resistance, freeze/thaw durability, etc.) is important since common road-surface issues such as material loss, gradation change, loss of crown, surface erosion, rutting, and potholes are directly related to the quality of materials used in such roadways (Skorsetch, et al., 2015). Granular material sources (aggregate quarries) produce aggregates with various qualities and various prices, and aggregate prices could vary significantly due to hauling costs that depend on quarry location, so finding a cost-effective high-quality aggregate source has always been a primary concern and a challenge for those involved with granular roadway construction and maintenance.

Since hauling of aggregate from longer distances increases construction and maintenance costs, it would be important to consider the possible benefits of using higher-quality materials construction of granular roadways and providing sustained performance with less maintenance over a relatively longer time duration. Increases in the number of maintenance activities for granular roadways may require road closure and result in life-cycle cost increase (Jahren et al. 2005), and use of low-quality (high fine percentage) aggregates could result in higher vehicle operating costs (e.g., fuel consumption, high maintenance cost, body damage, and lower car durability). Moreover, use of low-quality aggregates may also result in fatigue, higher dust emission, and dust penetration into engines and other vehicle components with possible increases in wear rates.

There is a lack of high-quality aggregate sources in United States, particularly in Western Iowa. Previous studies have reported that aggregate sources located in northeastern Iowa can supply higher-quality aggregates than those from other regions such as the western and southern portions. Anecdotally, use of only half as much higher-quality aggregate can produce roadway performance equivalent to that of low-quality aggregate).

During the early 1960s, a sizable portion of the total public road network in Norway consisted of mostly unpaved gravel roads with low bearing capacity, carrying annual average daily traffic (AADT) of 50-400 vehicles. With the arrival of the spring-thaw period, these roadbeds softened, and many road sections became impassable for all vehicles, irrespective of weight. Considering the prevailing practices at that time, these road sections would normally have required reconstruction before applying bituminous surfacing (Overby and Pinard 2007; Pinard 2013), but the road rehabilitation program progressed slowly because of budgetary constraints and difficulties associated with setting up heavy construction plants (Overby and Pinard 2013). This situation led to a desire for developing a faster method/treatment that could improve gravel-road quality at relatively lower cost (Overby and Pinard 2007). The Norwegian Road Authorities preferred that such a surface treatment should be cost-effective to provide a faster return on investment, should perform (as perceived by the road user) in a manner similar to conventional bituminous surfacing, and should comply with the following requirements (Overby and Pinard 2012):

- Be inexpensive and easy to implement;
- Utilize locally-available aggregates;
- Mitigate water penetration into moisture-susceptible base materials;
- Be very flexible, durable, and easy to maintain.

Although Otta seal was originally intended to be used only as a temporary bituminous surfacing for unpaved gravel roads with low traffic volume, its good performance led to its being used as a beneficial permanent surfacing technique for both newly-constructed and existing asphalt roads and for both low- and medium-traffic situations. From 1965 until 1985, more than 12,000 km of unpaved roads, approximately 20% of the total Norwegian road network, have been surfaced using Otta seal. Although the amount of Otta seal construction has been rapidly increased in the Nordic countries, Asia, Africa, and South America (Kelly and Juma 2015), its use in the US has been rather limited due to a lack of knowledge and the limitations of the empirical design approach associated with this technique. Since Minnesota, Iowa, and South Dakota are the only three states that have currently completed Otta seal projects in the North America (Ceylan et al. 2018; Gushgari, et al., 2018; Johnson 2003), further economic analysis and evaluation of trials or demonstrations would be desirable as part of the implementation process before further Otta seal deployment. An existing study (Overby and Pinard 2013) has reported Otta seal's lower life-cycle costs compared to other bituminous surface treatments (BSTs), but the weakness of the study lies in its assumptions. A deterministic analysis of life-cycle costs assumed particular costs for the materials used in the surface treatment. But assuming that today's cost of liquid asphalt binder would be inflated at an annual rate of 3% to 5% over a period of a decade or more could be a fundamental mistake. Since the prices of diesel fuel and of bituminous products have nearly tripled over the past decade and such instability implies that deterministic economic analysis cannot be performed with any degree of confidence when applied to highly-volatile construction materials (Gransberg and Scheepbouwer 2010). In addition, Previous studies have also shown that annual maintenance costs for a gravel road increases as the AADT increases (Skorsetch et al. 2015), and because there is a general trend toward increasing traffic volume, especially in urban areas, further studies that included traffic volume in determining the best times for upgrading roads to surfaces with BST were recommended (Jahren, et al., 2005).

Problem Statement

Many aspects of the nation's infrastructure are in dire need of improvement, as effectively illustrated by the American Society of Civil Engineers (ASCE) and its Infrastructure Report Card. As of 2017, the ASCE gave American infrastructure a cumulative grade of D+ ("poor"), unchanged from the previous report card published in 2013. In its reports on individual categories of infrastructure, the ASCE has expanded on problems that have contributed to this poor grade. For example, they gave a D grade in the category of Roads, citing such problems as "traffic delays costing the country $160 billion in wasted time and fuel in 2014" and "one out of every five miles of highway pavement is in poor condition". A D grade was also given to the nation's aviation sector, because aviation infrastructure (including airports and traffic control systems) was deemed to be lagging far behind advancements in aircraft technology, leading to increased congestion and a projected “$42 billion funding gap between 2016 and 2025”.

Decision-making techniques are useful tools for overcoming economic issues in engineering projects; the choice of a suitable decision-making technique is in itself a critical decision because different techniques may yield different solutions. It is imperative for a decision maker to be aware of the underlying principles of a technique as well as its associated pitfalls. In other words, the proper application of civil engineering economic analysis demands particularly great expertise. The development of economic analysis tools that are widely applicable to a variety of engineering projects is also a broadly important endeavor for use in the civil engineering field.

Heated Pavement Systems

Every year, large expenditures are dedicated to the maintenance of transportation infrastructures like highways and airport runways. Beyond typical maintenance, the winter months can bring additional costs in the form of ice and snow removal that is both labor and resource intensive. Traditional snow removal involves the use of vehicles and machinery that require considerable amounts of fuel and may also have consequential impact on the environment. Delays in snow removal can also contribute to major financial repercussions from lost productivity when major transportation hubs are shut down, preventing normal flow of work and business. Heated-pavement systems (HPS) are novel technologies for snow melting that support overall infrastructure maintenance. Various forms of HPS integrated into roadways utilize geothermal energy, natural gas, or electricity to melt snow and ice with minimal intervention required of snow-removal vehicles. However, even though HPS seems like a more promising and efficient method of winter maintenance than traditional methods, upfront costs of HPS installation constitute a barrier that can prevent serious consideration of its large-scale implementation by transportation agencies, especially those subject to tightly-constrained budgets.

Life-cycle benefit-cost analysis (LCBCA) can provide an important input to decision-making processes for new infrastructure systems, because it can carefully analyze expected benefits and costs (Gransberg and Scheepbouwer 2010; Stephan and Stephan 2017). Monetizing resilience benefits of an electrically-conductive concrete heated-pavement system (ECON HPS) in a LCBCA framework can provide a broader assessment of benefits from such systems and thereby help determine more cost-effective methods for building infrastructure resilience.

Low-volume roads

Federal funding has tended to focus more on building new facilities rather than in maintaining and improving existing infrastructure (Saeed 2006). State and local governments have jurisdiction over almost 97 percent of all roads and streets in the United States, and from 1953 to the present time total road and street mileage has increased by about 18.3 percent while paved mileage has increased by 183 percent (Federal Highway Administration 2014). Since much required infrastructure is already in place, getting better value from current roads ought to be prioritized. According to an FHWA 2016 budget estimate "the percentage of funding applied to new construction is decreasing while funds for rehabilitation of the system are increasing" (FHWA 2015).

With reductions in building new roads, while further deterioration of the system is anticipated if current policies are continued (Weingroff 2013), existing infrastructure systems could be maintained in a cost-efficient manner by implementing a preventive maintenance program (Federal Highway Administration 2014). Pavement preventive maintenance is defined as "a program strategy to arrest light deterioration, retard progressive failures, and reduce the need for routine maintenance and service activities" (FHWA 2007). The objective of such strategies is to apply remedial treatments before pavement deterioration to increase pavement service life. An effective pavement preservation strategy consists of series of various treatments (Geoffroy 1996). This study evaluated various aggregate options for low-volume Iowa roads to develop the most cost-effective aggregate option, and also investigated feasibility of using Otta seal implementation as a bituminous surface treatment.

The U.S. has approximately 1,417,000 miles of unpaved secondary roads that experience relatively low daily traffic volume, and to maintain such roads, U.S. county secondary road departments spend millions of dollars annually for aggregate replacement alone. While many international studies have described Otta seal as a low-cost bituminous surface treatment (BST) and dust mitigation technique, only three U.S. states – Minnesota, Iowa, and South Dakota – have reported on its construction and performance. In consideration of such limited use in the US, Otta seal might usefully be compared with chip seal - a commonly used BST in the U.S - from an economic-viability perspective. Therefore, a case study was conducted, with Minnesota and Iowa locations chosen for life-cycle cost analysis. Even though previous studies have shown that annual maintenance costs for a gravel road increase as the AADT increases (Skorsetch, et al., 2015), there has been a general trend toward increasing traffic volume, especially in urban areas, so further traffic-volume studies to determine the best times for upgrading roads to surfaces with BST were recommended (Jahren et al. 2005). Therefore, as another part of this study, a traffic-volume based economic analysis was conducted on two gravel roads exhibiting different annual daily traffic in Minnesota and Iowa counties to study average daily traffic volumes (ADT) and annual average daily traffic (AADT) patterns for evaluating cost-per-mile trends as traffic on gravel roads increases.

Objective

The goal of this research is to develop an economic decision-making framework for application to several infrastructure systems. The development of decision-making tools, widely-applicable to a variety of engineering projects, is a broadly important endeavor in the civil engineering field. The objectives of this research are described in the following subsections.

Heated pavement systems

The objectives of this research are to:

- Assess the economic feasibility of Hydronic Heated Pavement Systems (HHPS) for apron applications in commercial airports
- Conduct energy cost analysis for HHPS application to apron areas
- Determine initial construction and operational costs of Electrically-Conductive Concrete Heated-Pavement Systems (ECON HPS) based on actual construction cost and field measurements data
- Investigate economic performance of ECON HPS at commercial airports that experience particularly harsh winters (thirteen airports in total)
- Estimate rate of return and expenditures for financing ECON HPS implementation at an airfield.

Low volume roads

The objectives of this research are to:

- Compare Otta seal with chip seal from an economic viability perspective
- Evaluate life cycle cost of surfacing and maintaining an gravel road upgraded to an Otta seal surface

- Develop a traffic-volume based economic analysis to identify the appropriate time for upgrading a gravel road surface to an Otta seal surface

Dissertation organization

This journal paper-based dissertation is organized as follows:

Chapter 1 includes a summarized background, research objectives, and dissertation organization.

Chapter 2 presents the first journal article: ***Towards Resilient Infrastructure Systems for Winter Weather Events: Integrated Stochastic Economic Evaluation of Electrically Conductive Heated Airfield Pavements*** that investigates the economic viability of electrically conductive concrete (ECON) heated pavement systems (HPS), based on construction and operational experiences with the first full-scale ECON HPS at a U.S. airport (Des Moines International Airport (DSM)). Monte Carlo simulation-based analysis was also conducted to quantify the most significant variables influencing the overall economic viability of ECON HPS. The results of analysis indicate that benefits of implementing this system would outweigh its costs with more than 70 percent reliability. The results of sensitivity analysis indicate that number of aircraft operations would strongly affect the benefit-cost ratio (BCR). The simulation was also designed and run for the Minneapolis-St. Paul International Airport, MN (MSP), which has six times more enplanements than DSM. The simulation results showed a 92 percent relative likelihood that the BCR ratio of implementing ECON HPS in MSP would be greater than one.

Chapter 3 presents the second journal article: ***Integrated Stochastic Life Cycle Benefit Cost Analysis of Hydronically-Heated Apron Pavement System.*** The main goal of this paper is to assess the economic feasibility of hydronically-heated pavements systems (HHPS), one type of heated pavements, for use at apron areas of commercial airports. Both benefits and expenses associated with use of HHPS for snow and ice removal were identified and quantified in monetary terms using a stochastic economic analysis method, and a sensitivity analysis approach was used to determine particular variables that significantly influence overall economic viability of HHPS. The findings suggest that, despite high capital costs, HHPS use at airports might be economically feasible. The results from the sensitivity analysis indicate that airport size, in the context of number of aircraft operations, strongly affects the benefit-cost ratio of HHPS use.

Chapter 4 presents the fourth journal article: ***Economics of Electrically Conductive Heated Airfield Pavements***. In this study, economic performance of ECON HPS is investigated through Monte Carlo simulation-based Life Cycle Cost Benefit Analysis (LCBCA) for the largest commercial airports in the US that experience harsh winter events. To this end, states that experience average annual snowfall of more than 635 mm (25 inches) were identified; costs and benefits associated with ECON HPS placement were determined for aforementioned case studies based on experiences obtained from the first full-scale ECON HPS implementation at Des Moines International Airport (DSM). The result of the analysis showed that Chicago O'Hare International Airport (ORD) would benefit the most from ECON HPS installation. In addition, for three case studies (i.e. Salt Lake City International Airport (SLC) and Denver International Airport (DEN) along with ORD), the benefit cost ratio (BCR) was bigger than one in all of the possible scenarios Finally, a stochastic sensitivity analysis was conducted to determine variables that have significant impacts on the overall economic performance of ECON HPS. The result of this analysis indicate that the duration of delays and number of aircraft operations along with construction costs have the most significant impact on BCR.

Chapter 5 presents the fourth journal article: **Deterministic and Stochastic Life-Cycle Cost Analysis for Otta Seal Surface Treatment**. In this paper using Minnesota as a case study location for life-cycle cost analysis, an analysis was conducted at two levels: (I) deterministic life-cycle cost analysis, and (II) stochastic life-cycle cost analysis. Based on results of these analyses, it was concluded that the Otta seal could potentially be an economic viable BST, and public agencies could use it to reduce maintenance cost of low-volume roads, especially when gaining access to uniformly-graded aggregate which is commonly used for chip seals is not viable.

Chapter 6 presents the fifth journal article: **Economics of Upgrading Gravel Roads to Otta Seal Surface**. In this paper, an economic analysis was conducted to compare the cost of maintaining a gravel road to the cost of upgrading an existing gravel road to a double Otta seal surface. This analysis was conducted at three levels: deterministic life-cycle cost analysis (LCCA), a stochastic Monte Carlo simulation based LCCA, and a traffic based economic analysis. A generic one-mile rural road in Midwest was considered as a case study location. Although, according to the analysis conducted in this paper, an upgrade to Otta seal investment might be justified by maintenance savings, relying only on financial justification cannot warrant investment in most cases and some other factors such socio-economic impacts may need to be considered. The upgrade from gravel road to Otta seal, or any other BSTs, might be justified in terms of enhancing safety for road users and also encouraging economic development beneficial to local areas.

Chapter 7 is dedicated to the general conclusion of the dissertation as well as key findings of the papers presented in chapter two through chapter six.

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CHAPTER 2. TOWARDS RESILIENT INFRASTRUCTURE SYSTEMS FOR WINTER WEATHER EVENTS: INTEGRATED STOCHASTIC ECONOMIC EVALUATION OF ELECTRICALLY CONDUCTIVE HEATED AIRFIELD PAVEMENTS

A journal paper published in Journal of Sustainable Cities and Societies

Abstract

The impact of ice and snow on transportation infrastructure adds significant expense to the U.S. economy through the cost of snow removal, pavement deterioration, and profit lost due to travel delays, particularly for airport travel. Therefore, alternative snow removal practices are needed to reduce the costs and increase resiliency of communities when faced with harsh snowfall conditions. This study investigates the economic viability of electrically conductive concrete (ECON) heated pavement systems (HPS), based on construction and operational experiences with the first full-scale ECON HPS at a U.S. airport (Des Moines International Airport (DSM)). Monte Carlo simulation-based analysis was also conducted to quantify the most significant variables influencing the overall economic viability of ECON HPS. The results of analysis indicate that benefits of implementing this system would outweigh its costs with more than 70 percent reliability. The results of sensitivity analysis indicate that number of aircraft operations would strongly affect the benefit-cost ratio (BCR). The simulation was also designed and run for the Minneapolis-St. Paul International Airport, MN (MSP), which has six times more enplanements than DSM. The simulation results showed a 92 percent relative likelihood that the BCR ratio of implementing ECON HPS in MSP would be greater than one.

Keywords: Resilient airfield pavement, electrically conductive concrete, hated pavement, snow and ice removal, stochastic life cycle cost analysis, Monte Carlo Simulation.

Introduction

Recent studies on resilient infrastructure systems have focused transferring pavements from passive into an active member of urban environment, examples are. photocatalytic pavement (Dylla and Hassan 2012), cool pavements (Qin 2015), and heated pavement systems (Tuan and Sherif 2004). Many studies have shown that airports are one of the key factors in the development of the U.S. economic growth (Brown and Pitt 2007; Hye-jin and Ye-kyeong 2016). They bring together people, jobs, facilities and all the other inputs necessary to create a sustainable transportation network. Current practices for airport snow removal in the U.S. involve both mechanical and chemical methods. Conventional snow removal systems involve use of a great number of snow-removing vehicles and spraying large quantities of de-icing and anti-ice chemicals on the surfaces (Baskas 2011). The use of such vehicles is labor-intensive and usually requires temporary closure of airport operations (Baskas 2011). De-icing and anti-icing chemicals also can cause damage to concrete pavement and possible contamination of water runoff from airports (Merkert and Mangia 2012; Monsalud et al. 2014; Shen et al. 2017). Some airports also restrict the use of such chemicals because of high costs of remediation (Shen et al. 2017). Timeliness can also play a crucial role in clearing snow and ice on an airfield, so the Federal Aviation Administration (FAA) has established guidelines for the maximum amount of time that should be taken to clear snow and ice (Shen et al. 2017). For aprons in particular there is a great deal of activity by baggage handlers, oil-refueling operations, and other ground staff activities; the blend of hardware and human activity at aprons can pose safety concerns under adverse winter conditions (Merkert and Mangia 2012).

To support resiliency in communities to regularly overcome otherwise debilitating winter weather-related challenges, new alternative technologies and materials are needed (Pan et al. 2015). These techniques include electrically heated pavement systems (EHPS) (Abdualla et al. 2016; Gomis et al. 2015; Sadati et al. 2017), hydronic heated pavement systems (HHPS) (Thurston et al. 1985), super-hydrophobic coating techniques (Arabzadeh et al. 2016a; b), and phase-change materials (Farnam et al. 2015). These technologies are developed to reduce environmental effects of deicers, costs of fuel and energy used, and travelers' delays. One type of EHPS introduced during the early 2000s for melting snow/ice is electrically conductive concrete (ECON) (Tuan 2008). ECON is made by adding conductive materials to Portland cement concrete mix. An ECON pavement system involves applying electrical energy through embedded electrodes, thereby letting the pavement itself serve as a heat source.

There are different possible conductive materials that could be used for ECON mix design, including steel shavings (Tuan 2008), carbon powder (Farnam et al. 2015), and carbon fibers (Abdualla et al. 2016). Among these options, carbon powder/granular materials are associated with a very high dosage requirement to achieve acceptable electrical conductivity, resulting in a reduction of concrete strength (Wu et al. 2014a) and high materials cost, especially in the case where nano-particles are used. The use of ECON fabricated with steel shavings has been previously investigated on a bridge deck project (Tuan 2008). Although steel fibers and shavings are very effective in resistive heating (Wang et al. 2008), the addition of steel fiber to a concrete mix results in drawbacks such as corrosion (Wu et al. 2014b), high dosage requirements (Tuan 2008), and prohibitions for use in airfield pavement (Shen et al. 2017). To the best of the authors' knowledge, large-scale implementation of ECON made with carbon fibers has not been reported in previous studies. In November 2016, two 4.5m × 3.8m ECON HPS slabs were constructed using carbon fiber at the general aviation apron at the southwest corner of the Elliott Aviation hangar on the north side of the Des Moines, Iowa, International Airport (DSM), as shown in Figure 2-1. This test setup represents the first full-scale electrically-conductive concrete ECON HPS at a U.S. airport.

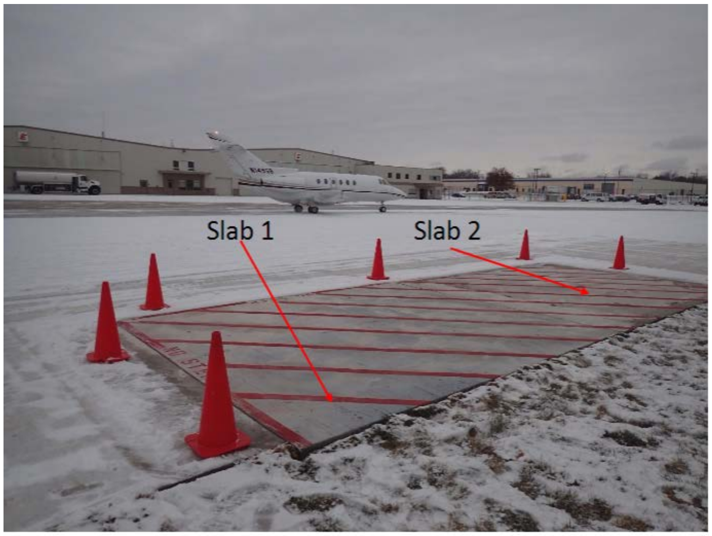


Figure 2-1 Electrically conductive concrete (ECON) test slabs built at Des Moines International Airport (DSM) (photo taken December 23, 2016)

Life-cycle benefit-cost analysis (LCBCA) is a major input in decision-making processes for new infrastructure systems, as this method analyzes the expected benefits and costs (Gransberg and Scheepbouwer 2010; Stephan and Stephan 2017). Monetizing resilience benefits of ECON HPS in a LCBCA framework provides an assessment of broader benefits from such systems, and helps determine cost-effective ways to build resilience into infrastructure. Therefore, this study has two main objectives. The first is to determine initial construction and operational costs of ECON HPS, based on actual construction cost and field measurements data obtained from the DSM test setup. The second main objective is to investigate economic performance, something not previously done for this type of HPS. Because ECON HPS has not been widely implemented and used in practice, it has not yet gained acceptance by the relevant sectors, so economic analysis studies using real project data would be timely for highlighting potential benefits and costs associated with this technology. DSM was considered as a case study for analysis since this small-hub (0.25% of aggregate U.S. enplanements) air terminal (BTS 2016a; FAA 2016) subject to a yearly snowfall of more than 89 cm. DSM handles more than 1.1 million enplanements per year, (BTS 2016a; FAA 2016) with daily operations of approximately 220 aircraft that annually transfer about 140 million pounds of cargo. The remainder of this paper discusses the study’s approach to stochastic life-cycle benefit-cost analysis (LCBCA), cost and benefit estimations, and model results.

Methodology

Deterministic (LCBCA) is the traditional decision-making method in pavement management (FHWA Pavement Division 1998). It involves using point estimates that result in a single output value. One fundamental factor in deterministic LCBCA is benefit-cost ratio (BCR), the ratio of net benefits to net costs of a project (FHWA Pavement Division 1998). A ratio greater than one of the sum of present values of benefits to the costs of the project implies a general economic argument supporting action to make the investment (FHWA Pavement Division 1998). The outcome of a deterministic LCBCA depends on numerous estimates, forecasts, assumptions, and approximations, each such factor potentially introducing error into the results. The impact of each error on the outcome of the BCR must be known to a decision maker if informed decisions are to be made with confidence (FHWA Pavement Division 1998; Gransberg and Diekmann 2004; Gransberg and Kelly 2008). Although some insight may be gained about variability of output when deterministic LCBCA is employed in conjugation with sensitivity analysis, such analysis is generally inadequate when applied to the construction industry that exhibits highly volatile costs (Gransberg and Scheepbouwer 2010; Pittenger, et al., 2012). An analyst not thoroughly acquainted with underlying engineering economic analysis theory may inadvertently choose input values that create invalid output (Gransberg and Kelly 2008). Particular issues associated with deterministic

LCBCA models, including sensitivity of the results to the chosen discount rate and the mismatch between the volatility of underlying commodity prices and an assumed constant rate would be addressed by developing a stochastic life-cycle cost model. The stochastic LCBCA approach, as used in previous studies for pavement management (Gransberg and Pidwerbesky 2007; Nahvi 2017; Pittenger et al. 2012; Reigle and Zaniewski 2002), was employed in this study to explore the cost effectiveness of ECON, as described in Section 2.1.

Stochastic LCBCA Model

The stochastic LCBCA approach uses Monte Carlo Simulation and allows input variables to vary through their probability distributions based on recent historical and regional changes (MCS) (Pittenger et al. 2012). Figure 2-2 denotes different components of the stochastic LCBCA model used in this study. First, expenses and advantages of introducing ECON HPS were quantified. Input values, such as costs, benefits, discount rate, and system lifetime could have many possible values, potentially resulting in a range of outputs. MCS supports quantification of the range of possible BCR values by performing sensitivity analysis to identify the impact of each input variable on the overall BCR model (Gransberg and Kelly 2008; Gransberg and Scheepbouwer 2010). Results are displayed using a probability distribution and a tornado graph, respectively, for BCR and sensitivity analysis. The major costs and benefits were itemized based on discussions with the Federal Aviation Administration (FAA) and Des Moines International Airports officials.

In addition, for the major cost items (i.e. initial and operation costs) costs were estimated based on field implementation, i.e. this information was obtained from the contractor and actual field measurements to the best of the ability of the research team.

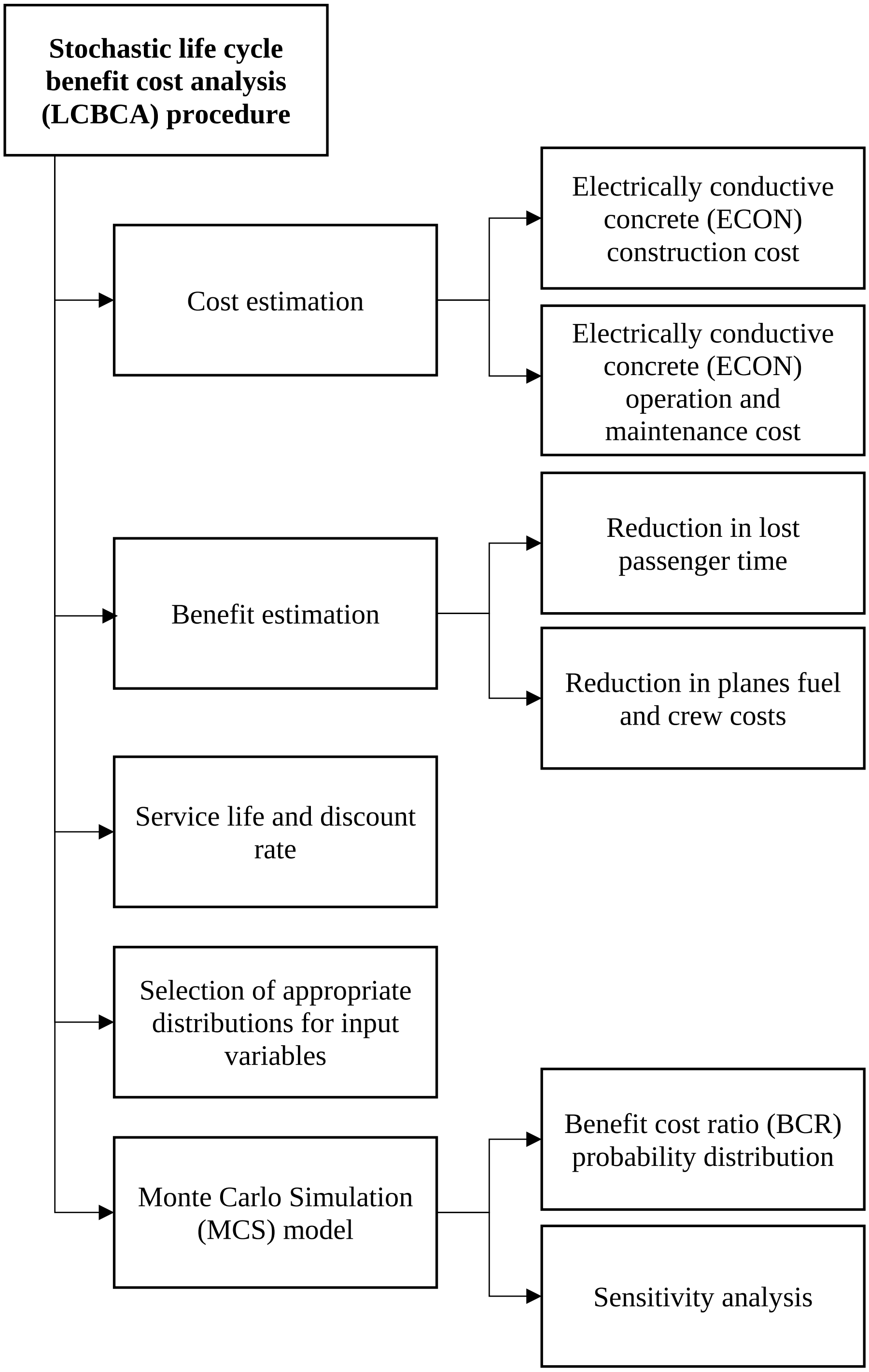


Figure 2-2 Components of the stochastic Life Cycle Benefit-Cost Analysis (LCBCA) model

ECON HPS Cost Estimations

The data required for ECON HPS cost estimations were collected during ECON HPS construction in November 2016 and operations during snow events from December 2016 to March 2017. Using these data, the unit costs of ECON material, construction, and operation were calculated and utilized for estimating costs under the assumption that the entire DSM apron area would be paved using ECON. Detailed cost estimations are provided in the following subsections.

ECON Material Cost

ECON should have a significantly higher conductivity than regular concrete in order to allow flow of electric current and generate heat when voltage is applied. To come up with a highly conductive ECON material, several sets of mix designs were investigated for utilization in DSM ECON HPS construction (Sassani et al. 2017). The final selected mix design contains 1% carbon fibers by volume of the total concrete mix. The cost of ECON material was estimated (cost and compared with the cost of regular Portland cement concrete (PCC), as shown in Table 1. The material cost of ECON is higher than PCC, mainly because of the use of carbon fiber, the largest driver of ECON costs. Based on the results of experimental studies (Sassani et al. 2017), 1% of carbon fiber is the lowest possible amount that can be added to the mix design to appropriately maintain electrical conductivity of the ECON at a level required for melting snow and ice under the winter conditions typically experienced at DSM. In addition to electrical conductivity, the thermal conductivity and specific heat capacity of ECON are also important in its thermal performance (Sadati et al. 2017). Thermal conductivity and specific heat capacity of ECON are measured to be in the range of 1.2 to 1.3 W/m.℃ and 1000 to 1300 J/kg.℃, respectively. ECON material properties are presented in detail in a previous study (Sassani et al. 2018).

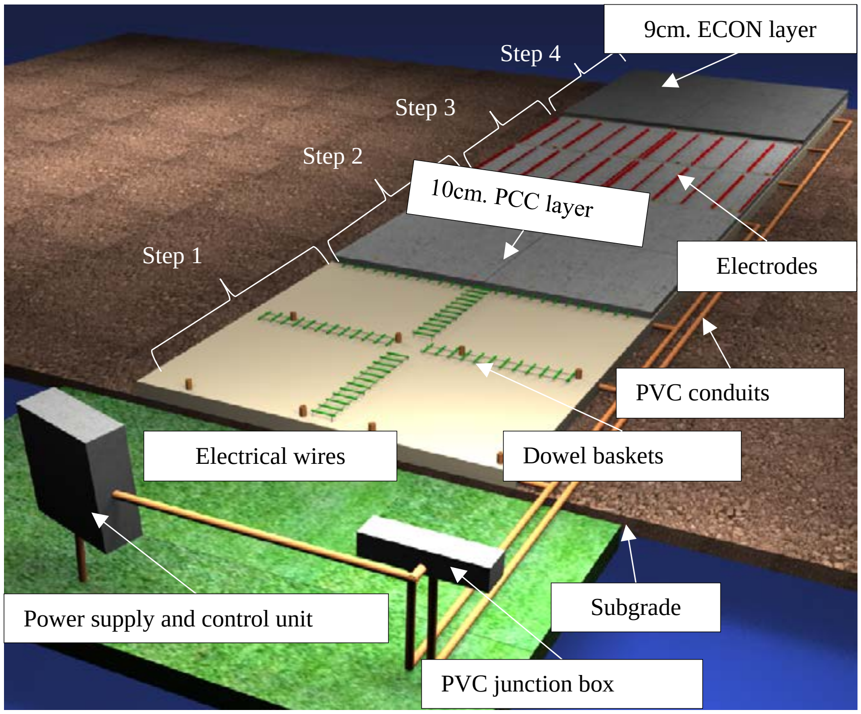
Table 2-1 Comparison of the material costs of electrically conductive concrete (ECON) and Portland cement concrete (PCC)

Materials	**Material Costs for PCC, 10 cm. base layer (USD/m^3)**	**Material Costs for ECON, 9 cm. top layer (USD/m^3)**
Carbon fiber *	-	110
Coarse aggregate	36	36
Fine aggregate	10	10
Cement	84	84
HRWR (high range water reducing admixture)	-	0.005
AEA (air entraining admixture)	-	0.25
Conductivity enhancing agent	-	0.25
Dispersive agent	-	29
Total	130	270

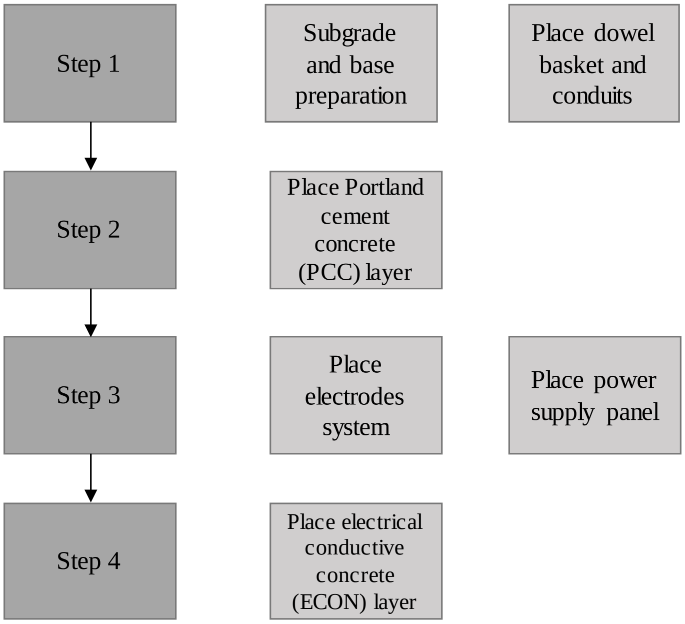
**Note that 70% of carbon fiber is 0.58-cm long and 30% is 0.30-cm long*

ECON HPS Construction Cost

To enhance the precision of cost estimation, a work breakdown structure (WBS) was developed and each work package's individual cost was determined. The WBS for ECON HPS can be divided into four major work activities, as presented in Figure 2-3. As shown in Table 2, construction costs for ECON HPS, from preparation to control system implementation, was estimated to be 396 USD/m^2.



(a)



(b)

Figure 2-3 ECON HPS field implementation: (a) Work sequence, (b) Work breakdown structure (WBS)

Although the ECON HPS construction cost was a critical factor in this assessment, there was no available standardized value because full-scale construction of ECON HPS made with carbon fiber had not previously been done. The cost value of 450 USD/m^2 obtained from actual ECON HPS construction at DSM was therefore utilized as the base value for calculating ECON HPS construction costs for the entire apron at DSM (139,355 million m^2 of pavement area). However, because there was uncertainty in installation costs, a need to capture cost variations due to different concrete thicknesses, and uncertainty related to the heating system, this item was taken as one of the input variables selected for sensitivity analysis. Specifically, costs ranging from 225 USD/m^2 (fifty percent lower than the base case) to 675 USD/m^2 (50 percent higher than the base case) were explored in the stochastic analysis.

Table 2-2 ECON HPS construction cost obtained from DSM field construction for two 17.5 m2 slabs (constructed November 2016)

Item No.	Item	Unit	Quantity	Unit Price (USD)	Total (USD)
	Step 1-Preparation for Concrete Placement				
1	Subgrade preparation	m^2	35.1	32	1,344
2	crushed aggregate base course, 20 cm	m^2	35.1	22	924
3	Dowel baskets	EA	8	65	520
	Step-2 Placing PCC				
4	10 cm PCC pavement	SY	42	85	3,570
	Step-3 Placing electrodes and ECON layer				
5	Electrodes (electrode size 3.8 cm × 3.8 cm × 3.65 m)	EA	12	65	780
7	9cm. ECON (17.7 USD/kg of carbon fiber)	m^2	35.1	150.5	6,321
	Step-4 Power supply box and control system				
8	Power supply box	EA	1	1,520	1,520
9	Remote control system	EA	1	320	320
	Total cost for two 4.5m × 3.8m slabs				15,299 USD

During the ECON HPS construction, in addition to the test slabs, 10 other regular 19cm concrete slabs were also implemented. According to the contractor ("Kingston Services" 2018), the cost of concrete placement for one slab (all costs, including general condition, mobilization, overhead, contingency and so on) would be about 5,000 USD. Figure 2-4 compares the cost of reconstruction for regular concrete with ECON HPS systems, showing that (according to the DSM field implementation) the construction costs of the entire ECON HPS system (from foundation to power supply elements) would be approximately 50 percent more than that of a regular concrete pavement system.

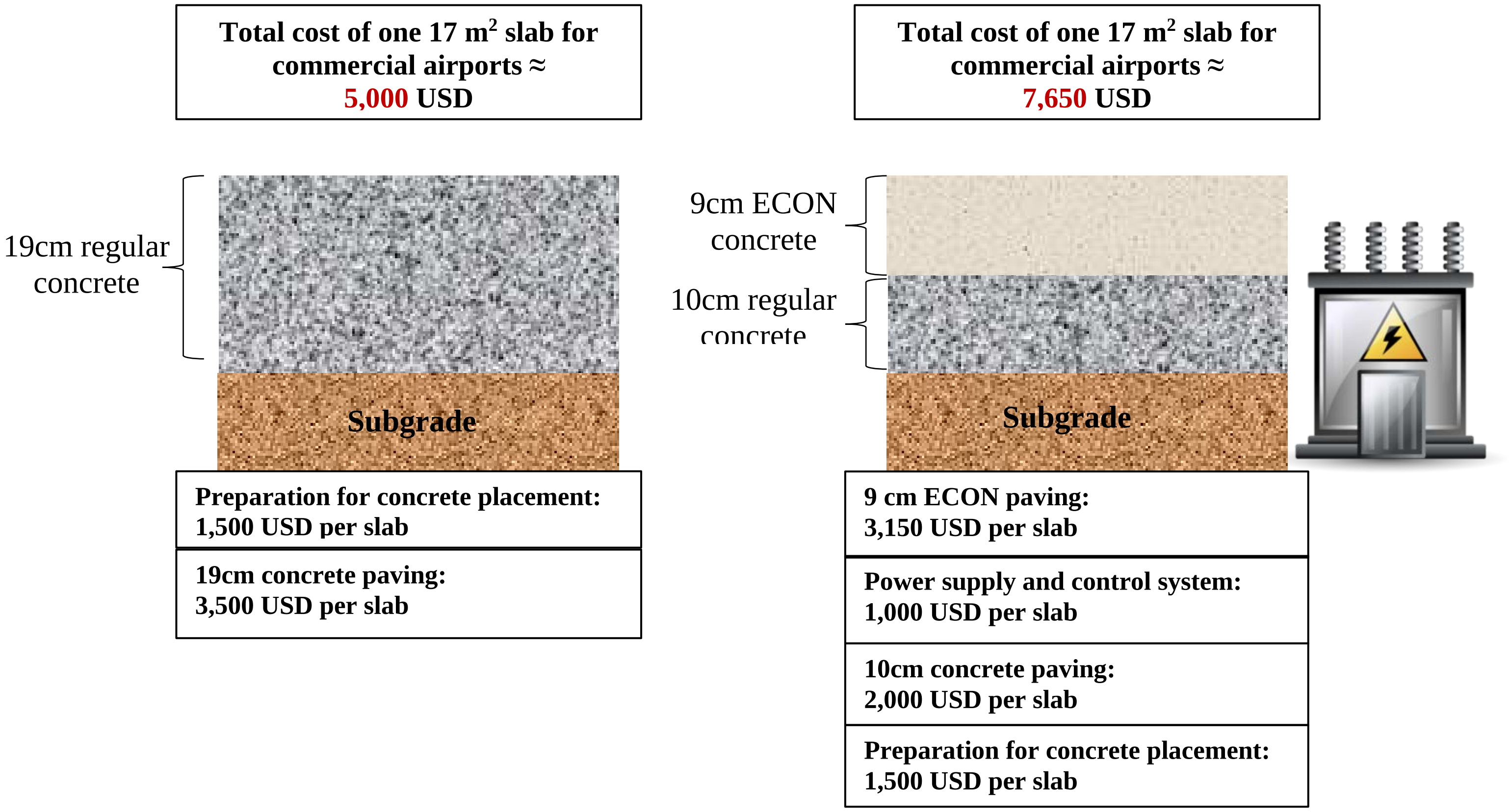


Figure 2-4 Costs associated with the construction of regular concrete slabs (4.5m × 3.8m) and the ECON HPS system

ECON HPS Operational Cost

ECON HPS operational electricity use was estimated from electric current and voltage measurements taken during from the constructed DSM slab operations for seven snow events, ranging between light to severe snow storms generally lasting 3 to 4 hours, and including arctic blast weather conditions that occurred on December 18 and 19 2016 (Weather Underground 2016). During each of these snow events, the ECON HPS was kept turned on for the entire snowfall duration. Ambient temperature measurements using wireless temperature sensors installed in DSM ECON HPS were performed and validated with those from an automated surface-observing system (ASOS) database (ASOS 2018).

Table 3 illustrates the measured electricity used during the system operations along with weather condition measurements and duration of each operation. An average electricity use of about 400 W/m^2 was observed for seven snow events with temperatures ranging from -4°C to -23.5°C recorded at DSM weather station (ASOS 2018). Note that electricity use of more than 7.69 kWh/m^2 was measured during arctic blast weather conditions, i.e. presence of ice on the pavement in -23°C ambient temperature which required the system to be in operation continuously for 18 hours.

Equation 1 was used to estimate annual operational costs of the ECON HPS for the entire DSM apron area,

$$A_c = E_c \times D_s \times N_s \times E_p \qquad (1)$$

Where A_c is Annual operational cost, E_c is the average electricity use (Wh/m^2) for one hour, D_s is the duration of a snow event (hours), *Ns* is the number of snowfall events in the winter season, and E_p is the average electricity price (USD) for the State of Iowa. Based on information taken from an ASOS database (ASOS 2018), durations and average numbers of snowfall events at the DSM international airport over the last five years were obtained. In addition, the commercial price of electricity in the state of Iowa for the years 2011 to 2015 was used as the unit price of electricity in this analysis (EIA 2016).

Table 2-3 ECON electricity use across seven snow events in 2016 and 2017

Date	Average temperature during the operation (°C)	Average wind speed temperature during the operation (m/s)	Accumulated snow thickness (cm)	Duration of each operation (hour)	Average energy consumption of test slabs (kwh/m2)
Dec. 10, 2016	-3.8	3.6	3.0	7	2.64
Dec. 18-19, 2017	-23.8	7.2	2.5	21	7.69
Jan. 25, 2017	-10	6.3	1.3	1.5	0.59
Feb. 08, 2017	-10	5.8	3.8	3.5	1.18
Feb. 24, 2017	-5.5	7.6	2.0	2.5	0.70
Mar. 13, 2017	-6.1	5.8	3.3	2	2.64

ECON HPS Maintenance (O&M) Cost

Based on information provided by DSM administration, the maintenance costs for a large-scale heated pavement system were taken to be 1% of its capital cost. Because ECON HPS had not previously been implemented on a large scale, there was no historical data regarding associated maintenance costs. While the use of ECON HPS would be anticipated to increase pavement durability by reducing the likelihood of freeze-thaw damage and eliminating durability issues associated with application of deicing salts on concrete pavement, maintenance of the electric heating system or electrode replacement (in case of rusting) could at the same time be costly, so this was considered to be one of the input variables used in the sensitivity analysis. Specifically, minimum maintenance costs ranging between a minimum of 0.5% and a maximum of 1.5% of capital costs were explored, with 1% assumed to be the most likely value.

Benefits Estimation

This analysis was conducted to compare the benefits of ECON to those of the conventional snow removal systems as the base case scenario. Because the benefits could not be separated into per-unit levels, they were assumed to be a function of the area considered.

Value of Lost Passenger Time

When considering delays, the FAA Air Traffic Organization defines flights delayed by 15 minutes or more to constitute delays. The Bureau of Transportation Statistics (BTS) provides publicly accessible data on several aviation operation components including monthly delays and delay causes for each airport. Another important factor is the value of time (VOT) for passengers that suffer delays. Specifically, passenger delay costs herein will be considered to consist of the opportunity costs of time lost due to weather-related delays at airports. These represent indirect costs because airlines generally do not offer any form of compensation, such as discounts on meals or hotels, due to weather-related delays (BTS 2016b).

There can be many causes of scheduled air service delays, including severe weather, air carrier, security, or National Aviation System (NAS) delays, or aircraft late arrival (BTS 2016b). Weather-related delays are typically due to strong winds, low visibility, and extreme snowfall (BTS 2015, 2016b). The focus of this study was delays due to snowfall, and most the delays during winter happen due to snowfall (WeatherBill 2017). Weather-related delays represent approximately 3% of the total number (BTS 2016b; WeatherBill 2017). Since delay-related data reported by the airlines is not detailed, there are uncertainties associated with this variable, so the percentage of weather-related delays was included as one of the input variables for sensitivity analysis in the stochastic cost model. Passenger costs associated with flight delays are based on air traffic demand, so the total number of aircraft seats available and load factor approximations were used to estimate demand. Load factor is a measure of the use of aircraft capacity that represents revenue passenger miles (RPMs) as a proportion of available seat miles (ASMs) (BTS 2017). The average total load factor for U.S. domestic flights for 2016 was 84.59 % (BTS 2017). Since the volume of air traffic does not remain constant but is expected to increase approximately every year, this study used an average annual traffic growth forecast of 2.8% over the next 20 years, based on the FAA recommendation (Schaufele et al. 2017).

To estimate this cost, passengers were grouped into two categories, those traveling for business and those traveling for personal purposes or leisure (Belenky 2011), and the different values depending on trip purpose are shown in Table 4. Based on the load factor and type of aircraft considered, an average load on a single flight of 74.5 passengers traveling for leisure and 50.5 passengers traveling for business was calculated (Belenky 2011). The average duration of weather-related delays during the previous five winter months was 45 minutes for DSM (BTS 2016b). Since durations of delays rise and fall irregularly, this item was also included as a variable in the stochastic LCBCA model to reflect the effect of duration of delays on life-cycle costs. Passenger delay costs can be calculated using Equations 2 and 3 (Anand et al. 2017; Belenky 2011).

$$T_d = N_d \times P_s \times P_g \times A_d \times 120 \qquad (2)$$

Where T_d *is* total delay hours in a season, N_d is number of daily operations, P_s is number of snow-related delays, P_g is passenger growth rate, and A_d is average duration of one delay (hours). The 120 value represents an average of 30 days in a month multiplied by 4 months in a season.

$$A_m = T_s \times L_f \times P_p \times T_p \times V_t \qquad (3)$$

where *Am* is annual monetary value of lost passenger time (USD), *Ts* is total number of seats in an aircraft, *Lf* is load factor, *Pp* is percentage of passengers based on trip purpose (leisure or business), and *Vt* is value of time based on trip purpose.

Table 2-4 Opportunity cost of time for passengers on a delayed flight

Value of time	Cost (USD/h)	Percentage Distribution (%)	Number of Passengers On a Flight
Personal	36.1	59.6	74.5
Business	63.2	40.4	50.5

Reduction in Planes' Fuel and Crew Costs

The number of delayed flights was calculated in the same way as for lost passenger time. Aircrafts can incur delays in three possible ways: mid-air, gate, and ground delays. Mid-air delays will result in the greatest amount of fuel waste, while the other types will be related only to idling fuel waste. According to the Airport Cooperative Research Program (ACRP) Report 123 (Mcgormley et al. 2016), mid-air delays are considered to cost 4,456 (USD/h), ground delays 2,148 (USD/h), and gate delays 1,442(USD/h), for an average of 2,850 (USD/h) suffered by airlines due to weather-related delays. The annual cost (for four winter months) imposed upon airlines due to weather-related delays can then be computed by multiplying this value by the total number of operations during those months. The annual growth rate of operations can also be accounted for in this case for subsequent years.

Service Life and Discount Rate

A critical parameter for ECON is its effective design life as a heated pavement. Similar to other studies on pavement management, service life was considered as projected number of years until rehabilitation is required (Balla 2010; Gransberg and Diekmann 2004). Service life uncertainty creates sensitivity in LCBCA results (Gransberg and Scheepbouwer 2010), making it a good candidate variable for stochastic analysis. A 20-year life cycle is recommended by FAA benefit-cost analysis guidance (FAA 1999), although there are uncertainties with respect to the service life of ECON HPS. On one hand, pavement durability might be increased due to the absence of deicing chemicals and elimination of snow removal equipment. In addition, modification of PCC with carbon fiber provides benefits in terms of mechanical performance and durability (Bazzaz et al. 2018; Cao and Chung 2001; Chen and Liu 2003; Graham et al. 2013; Peyvandi et al. 2013; Shu et al. 2015) , and hence reduces the contribution of maintenance operations to the carbon footprint of the pavement (Wang et al. 2016). while on the other hand, ECON HPS performance depends significantly on the electrical conductivity of the ECON material that has been found to decrease over time (Javier Baeza, et al., 2010; Shi 2004; Wang, et al., 2008) and diminish the performance of ECON HPS over time. The electrical resistivity of concrete does, however tend to become more stable with age; the resistivity typically stabilizes within a few months of hydration if the concrete is suitably cured (Liu and Beaudoin 1999**).** Since there is no available historical data about the performance of ECON HPS, three different service life values: 15, 20 and 25 years, were considered for the analysis. Federal Reserve (Federal Rserve 2018) discount rate data for the previous twenty years were also added to the model.

Selection of Appropriate Distribution of Variables

Determining the appropriate probability distribution for each input variable is an important step in the stochastic LCBCA approach. In this study, based on the availability of data for different variables, two methods were used to identify a probability distribution for each input variable. Variables with sufficient data availability (i.e. discount rate, duration of delays, electricity price, electricity consumption, duration of snow events, number of snow events in a year) were fitted to a distribution using a maximum-likelihood method. A chi-squared goodness-of-fit test was used to determine the distribution with the best fit (Pearson 1992). Discount rates for the previous twenty years (Federal Rserve 2018) were also fitted to a distribution, as were records reflecting the last five years in the State of Iowa for duration of delays, number of snow events, and electricity price (ASOS 2018; BTS 2016a; EIA 2016).

For the other input variables associated with limited historical data, a triangular distribution was used, conforming to a common method for describing the distribution of such variables (Gransberg and Diekmann 2004; Gransberg and Kelly 2008; Pittenger et al. 2012). In this study, these variables included service life, initial construction cost, maintenance, and percentage of weather-related delays.

Results of Stochastic LCBCA

As mentioned in the methodology section, a triangular distribution was used for variables associated with limited sample data, while variables obtained from field measurements or through historical records and reflecting the best fitted distributions are shown in Table 5. Standard deviations were also calculated to represent the amount of variation in each data set.

Table 2-5 Variables distributions for Monte Carlo simulation (MCS)

Input variable	**Distribution**	**Standard Deviation**	**Description**
Discount rate (%)	Pareto	1.1	α = 3.1
E_p - Electricity price (USD)	Weibull	0. 3	α = 5.5 β = 0.10
E_c - Electricity use (Wh/m^2)	Lognormal	25	μ= 401
N_d - Number of operations in each day (-)	Normal	23.3	N= 9,586, μ= 198
D_s - Duration of snow events (minutes)	Normal	52.5	N= 59, μ= 194
A_d - Duration of each delay (hours)	Normal	0.21	N= 235, μ=0.78
T_p - Trip purpose (-)	Discreet	N/A	59.6% personal 40.4% business

Figure 2-5 shows the probability density function for the BCR at DSM, with the area of distribution where BCR is greater than one highlighted in green. As shown in Figure 2-5, the relative likelihood that in implementing ECON benefits would outweigh costs is 72 percent. The estimate representing a two-tailed 90% confidence interval ranges from 0.76 to 1.98, with a median value of 1.23 and a standard deviation of 0.40. The median is a good measure because, irrespective of the shape of the distribution, half the population is below and half is above the median (Gransberg and Kelly 2008).

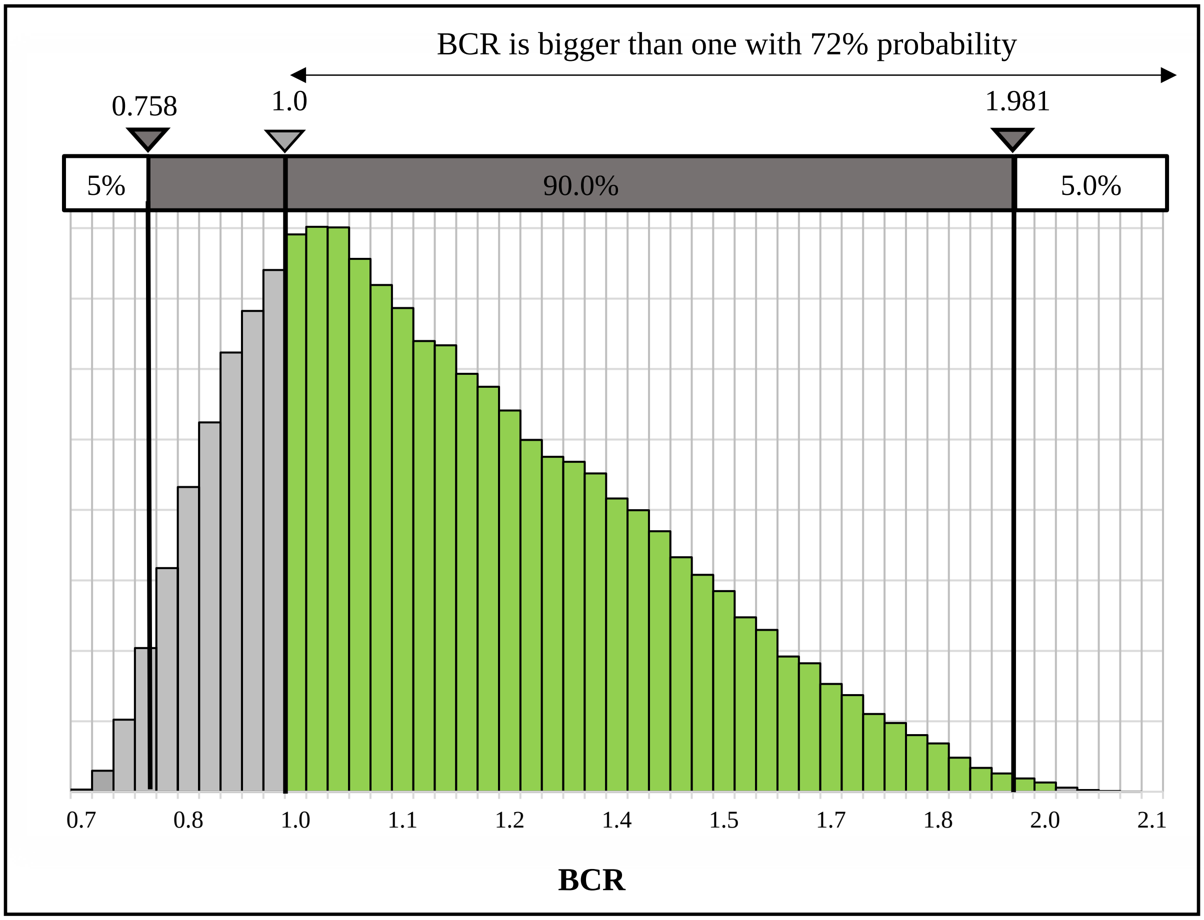


Figure 2-5 Monte Carlo simulation (MCS) probability density function results for benefit cost ratio (BCR) when electrically conductive concrete (ECON) is implemented over the entire apron area

Another objective of running a MCS-based sensitivity analysis (SA) is to determine which, among all the input variables, has the greatest potential impact on the overall BCR. Figure 2-6 shows the sensitivity analysis results using MCS. The figure presents a tornado graph that shows the SA results using a one-at-a-time (OAT) method in which one input variable at a time is considered to vary within a predetermined range, while all others remain at values chosen for the initial analysis, as discussed in the previous section.

Based on these results, the initial construction cost was found to be the key factor influencing the BCR, and it is anticipated that the BCR value would decrease as the initial cost of construction of ECON HPS increases. In addition, delays are naturally unpredictable because they depend on numerous factors such as weather, preparedness of airports, and airline procedures. The nature of delays may change drastically each year, so a sensitivity analysis was warranted to determine their influence on the BCR. Figure 2-6 also reflects that, interestingly, ECON HPS operational costs (i.e. maintenance and electricity consumption) have an insignificant impact on the life-cycle cost compared to the other variables considered.

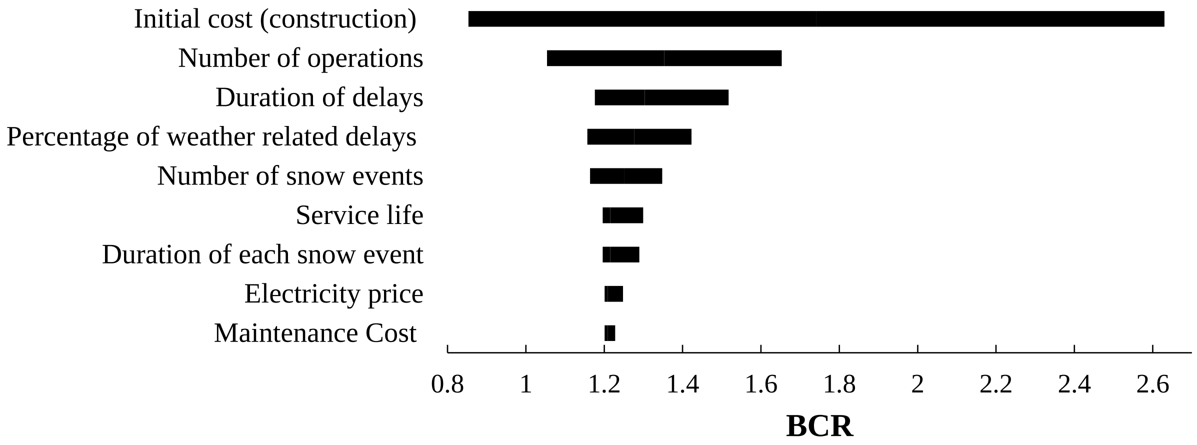


Figure 2-6 Tornado graph of Monte Carlo simulation (MCS) based sensitivity analysis results for the studied variables

The results of the analyses show that, since reductions in passenger delays and aircraft operating delay costs seem to drive the benefits of the ECON HPS at all airports, it is logical that the size of the airport in terms of operations would strongly affect the BCR of ECON HPS. To investigate how the number of operations influences BCR using an actual example, the Minneapolis-St. Paul International Airport, Minneapolis, MN (MSP), was selected for further analysis. MSP represents the case of a large hub airport with nearly 17 million enplanements in 2016 (1% of total U.S. enplanements) (FAA 2016). Approximately 1,200 daily aircraft operations in MSP were reported in 2016 (BTS 2016a), six times more than in DSM. In addition, MSP has 464,500m^2 of paved apron area, approximately 3.3 times more than DSM. To conduct the analysis, the same set of assumptions for initial cost of ECON HPS, including the percentage of weather related delays, discount rate, and electricity use for operating ECON HPS during snow events, were considered. Durations of aircraft delays for MSP were approximately 10 percent higher than for DSM, and the number of aircraft operations at MSP between 2011 and 2016 were used as model inputs (BTS 2016b). The duration and number of snow events from 2011 to 2016 were also collected from an automated surface-observing system (ASOS) database (ASOS 2018). The price of electrical power in Minnesota from 2011 to 2016 was obtained from U.S. EIA data (EIA 2016).

Figure 2-7 shows the probability density function for the BCR at MSP. As shown in the figure, the relative likelihood that the benefits of implementing ECON in MSP would outweigh its costs is 92 percent, 20 percent more than for DSM. The estimated BCR range with a two-tailed 90% confidence interval ranges from 0.94 to 2.36, with a median value of 1.76.

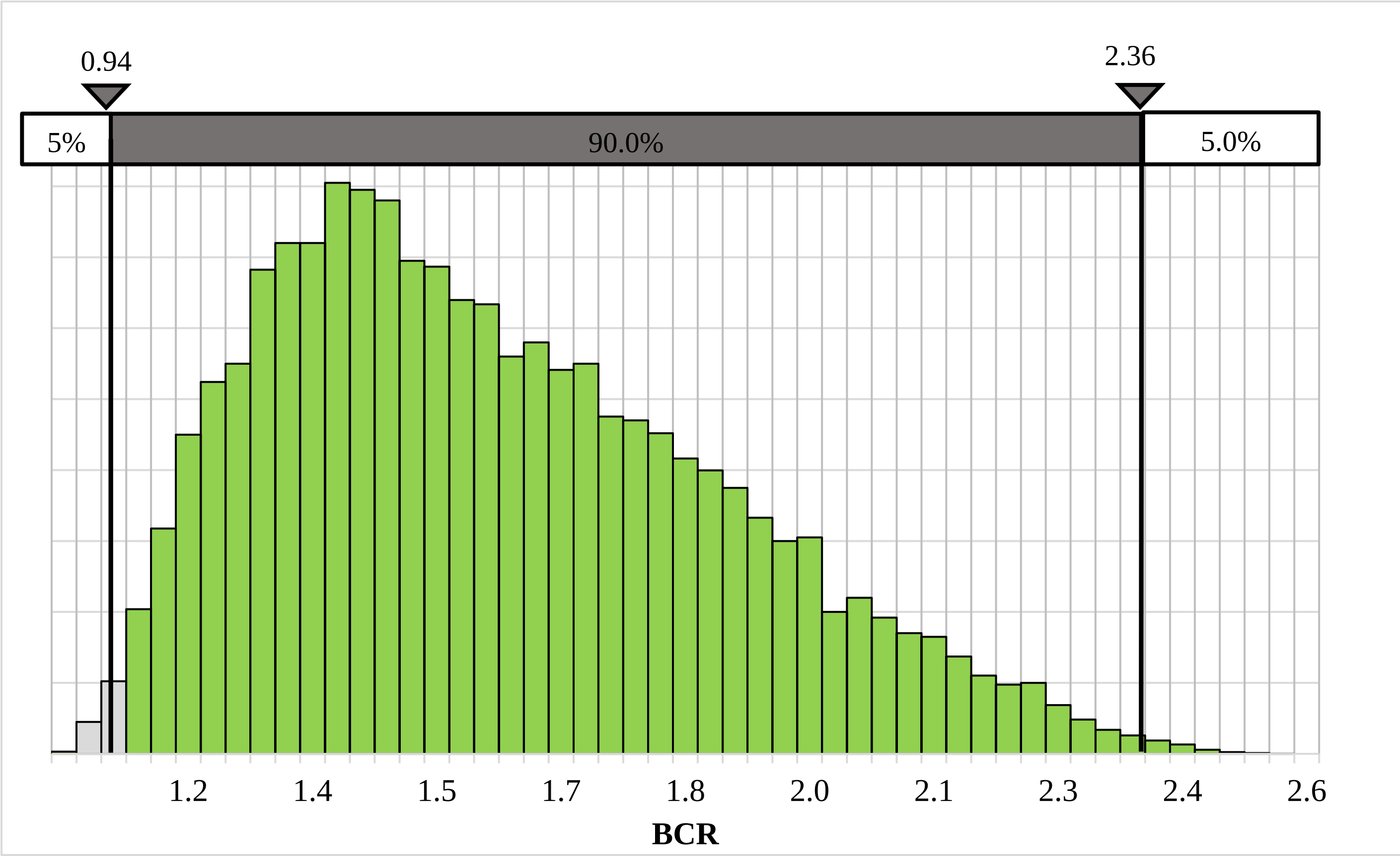


Figure 2-7 Probability density function results for benefit cost ratio (BCR) for Minneapolis-St. Paul International Airport (MSP)

While differences found for MSP are most likely due to the size of the airport in terms of aircraft and passenger operations, there is a possibility that the difference in probability density of BCR is the result of changes in other input variables (i.e. changes in duration of delays, number of snow events, and electricity price), so to determine the actual impact of input variables on the overall BCR, sensitivity analysis was performed, and Figure 2-8 shows the results of sensitivity analysis conducted for MSP.

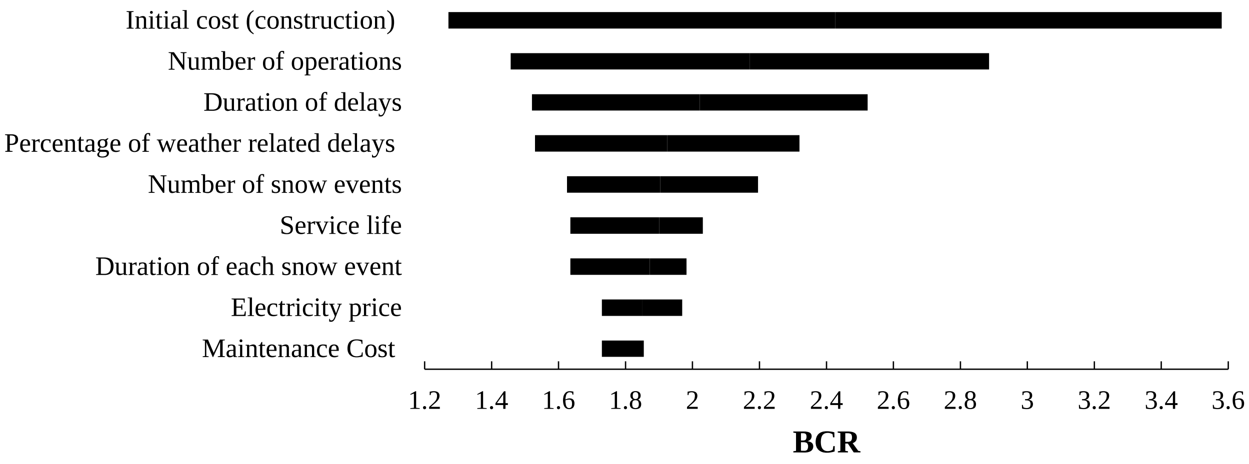


Figure 2-8 Tornado graph of Monte Carlo simulation (MCS) based sensitivity analysis results for the studied variables for Minneapolis-St. Paul International Airport (MSP)

As anticipated, similarly to DSM, the BCR for MSP was most heavily impacted by initial construction costs. As shown in Figure 2-8, unlike for DSM, both the number of operations and the duration of each delay have a significant impact on BCR (Figure 2-6), mainly because of the increase in number and duration of delays in MSP.

In fact, the initial construction cost is the only factor that by itself could drive the BCR below one for the DSM case. While the findings of both analyses suggest that the cost-benefit of ECON HPS in smaller airports (such as DSM) appear to be more sensitive to this initial construction cost, more analysis is needed in future studies to further study these differences across different airport scenarios.

It is conceptually possible that the installation of ECON HPS in only a portion of the aprons could be sufficient to clear snow and ice and create safe conditions for operations performed in the area. This could be accomplished by identifying the main areas of operations (both aircraft and staff) through site investigations and experimental studies and then strategically placing ECON HPS in these locations. Apart from the direct increase of benefits to be expected from increased operational efficiency, it is also possible that economies of scale can affect the economic analysis results. This element, however, was not directly assessed in this analysis and is anticipated to be the subject of future work.

Conclusions

The main goal of this study was to perform a life-cycle benefit cost analysis (LCBCA) to examine the viability of electrically conductive concrete heated pavement systems (ECON HPS). This study quantifies both costs and benefits of ECON HPS and provides decision-makers with enhanced information for making decisions related to alternative airport snow-removal strategies. The key findings of this study can be summarized as follows:

- Electrically conductive concrete-heated pavement systems (ECON HPS) can be a viable option from economic perspectives for achieving pavement surfaces free of ice and snow without using mechanical or chemical removal methods. ECON HPS may be particularly beneficial at aprons that may have a relatively small surface area relative to an airport’s total paved surface area, but if not cleared adequately, may have significant potential for causing winter weather-related delays.
- The identified benefits of ECON HPS implementation include reduction in lost passenger time and minimization of aircraft fuel wastage, exceeding costs of construction with 72% and 92% reliability, respectively, in the DSM and MSP cases.
- The cost-benefit of ECON HPS largely depends on the size of the airport examined, both in terms of the number of aircraft operations that directly affect the benefits of using ECON HPS, and the pavement area that affects the ECON HPS costs. In the MSP case, the number of operations and duration of each delay had a significant impact on BCR.

- Construction cost was the most sensitive variable impacting the benefit-cost ratio (BCR) of ECON HPS. Based on test section construction costs, while the construction cost of ECON would be approximately 50% higher than regular PCC, it is expected that advancements in ECON technology (e.g., improvement of electrical conductivity of ECON) and construction practices (e.g., increasing contractor knowledge of ECON technology) could significantly reduce these initial construction cost estimates.

There are several limitations of this study. This study estimated the economic impact of installing ECON HPS only for domestic flights; because the main airport studied (DSM) does not cater to a significant number of international flights. Costs of international delays are more difficult to estimate due to their more complex routing and requirements for communication of delay information. Such delays may be considered in future studies. In addition, the potential of increases in the number of airport operations after installing ECON HPS (i.e., induced demand) have not been considered in the analysis, and this could further magnify the expected benefits. Even without such speculation, it is believed that HPS would be likely to reduce delays and improve the efficiency of daily aircraft operations, thereby having a direct effect on revenue. Also, since airports do not normally employ snow-removal personnel for airfield work, with most having snow teams made up of maintenance and operations personnel that train together to do the required work on airfields, it was challenging to estimate the true benefits of elimination of machinery and labor costs associated with conventional snow removal.

This study also did not consider the potential for ECON HPS benefits to mitigate cargo delays, because each airport has different policies dealing with cargo and the frequency of cargo movement varies significantly by airport, making it challenging to collect information on cargo delays. Airports usually do not have such information in an accessible database; it can only be obtained from the cargo carriers themselves. Larger airports usually handle more cargo that is subsequently transferred to other states and countries or routed to smaller airports in the states. Finally, this study provides a justification for the use of ECON HPS on aprons; some airports may benefit from heating non-apron areas of the airports as well, while others may benefit most from installation of ECON HPS only in portions of the aprons, so it is crucial to also examine the relative benefits and costs of heating other pavement areas such as runways and taxiways. It would also be important to examine strategic placement of ECON HPS that could reduce installation costs without significant sacrifice of benefits. For example, the apron area at MSP is 5 million ft^2, and it is possible that only a portion of it requires heating. The methodology described in this paper could either be scaled up to explore an economic analysis of installing ECON HPS in the total paved area of an airport, or scaled down to study the impacts of partial-apron coverage.

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CHAPTER 3. INTEGRATED STOCHASTIC LIFE CYCLE BENEFIT COST ANALYSIS OF HYDRONICALLY-HEATED APRON PAVEMENT SYSTEM

A journal paper published in Journal of Cleaner Production

Abstract

Transportation infrastructure is greatly impacted by ice and snow, adding enormous costs to the American economy. Because of their sustainability benefits, heated-pavement systems (HPS) continue to gain attention as a potential alternative to conventional snow removal operations, and the main goal of this paper is to assess the economic feasibility of hydronically-heated pavements systems (HHPS), one type of heated pavements, for use at apron areas of commercial airports. Both benefits and expenses associated with use of HHPS for snow and ice removal were identified and quantified in monetary terms using a stochastic economic analysis method, and a sensitivity analysis approach was used to determine particular variables that significantly influence overall economic viability of HHPS. The findings suggest that, despite high capital costs, HHPS use at airports might be economically feasible. The results from the sensitivity analysis indicate that airport size, in the context of number of aircraft operations, strongly affects the benefit-cost ratio of HHPS use.

Keywords: Winter airport operations; Hydronically Heated pavement systems; Stochastic economic analysis; Monte Carlo simulation; Sensitivity analysis.

Introduction

In recent years, there has been a stronger focus on either investing in new infrastructure systems or retrofitting existing infrastructure systems designed and operated to be more resilient to natural and/or man-made extreme events (de Azevedo et al., 2018; Erker et al., 2017; Li et al., 2018; Rochas et al., 2015; Valenzuela-Venegas et al., 2018). Uninterrupted operation of critical transportation infrastructure systems like airports during such events is essential (Chang et al., 2014). Flight delays are a widespread challenge impacting the economy of every country, including the United States, and it is estimated that transportation delay costs came to approximately 32.9 billion dollars in 2007; it was estimated that this translated into a nearly 4 billion dollar reduction in the U.S. gross domestic product (Ball et al., 2010). Approximately one-third of delayed flights, including in the winter season, between September 2016 and August 2017 in the U.S. were due to weather conditions (U.S. Department of Transportation, 2017). Removal ice and snow from paved surfaces at airports is typically done by snow removal machinery and treatment of pavement surfaces with deicing and anti-icing chemicals (Baskas, 2011), and such conventional procedures are both labor-intensive and time-consuming, with deicing chemicals potentially causing long-term durability issues for pavements (Shi et al., 2009). Moreover, chemicals can contaminate water runoff from airports and thereby negatively impact the environment (Shen et al., 2017; Wang et al., 2006). Since addressing such socio-economic issues could help expand the set of experiences involving cleaner production, a sustainable alternative method for ice and snow removal would be most desirable in helping reduce transportation delays and consequently improving the U.S. economy. According to (Xu et al., 2018) hydronically-heated pavement systems are cleaner and more sustainable alternatives to the conventional ice and snow removal methods. Moreover, safety concerns due to snowfall and frost could also be addressed by HHPS installation.

The Federal Aviation Administration (FAA) has established operation-time-related criteria for clearing ice and snow related. For example, commercial airports with a number of airplane operations representing more than 40,000 passengers should be equipped to clear one inch of snow or ice from Priority 1 areas, i.e., runway, taxiways, and aprons (FAA, 2016), within one half hour. Since apron areas typically require increased labor-intensive activities such as luggage handling and plane refueling, using smaller-sized equipment there could also make the snow removal process slower and less effective, propagating delays, and there are safety concerns on aprons particularly due to the presence of labor-related activities associated with snow-removal machinery. Such issues may inspire the use of pavement heating, especially at apron locations. To overcome winter maintenance-related problems such as environmental effects of de-icers, fuel and energy waste, safety concerns, and traveler delays, two possible heated-pavement solutions have been proposed in recent literature: (1) electrically-conductive concrete (Abdualla et al., 2016), and (2) hydronically-heated pavement systems (HHPS) (Pan et al., 2015). This study explores the use of HHPS, the most mature of such technologies with which construction contractors have greater familiarity.

“Hydronic heated pavement surfaces may be achieved by circulating heated fluid through a series of pipes running beneath the pavement” (Liu et al., 2007) (Figure 3-1). Boilers fueled by natural gas or geothermal energy are typically used to supply warm water for such systems.

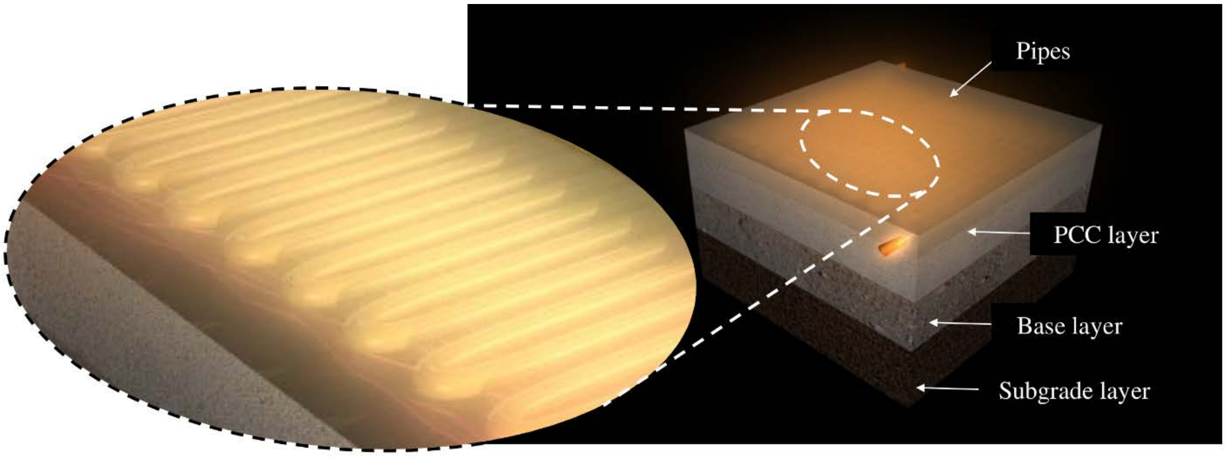


Figure 3-1 Details of a hydronically-heated pavement system (HHPS)

Application of HHPS for ice and snow removal operations has been reported as being effective and successful in European transportation infrastructure systems; in the U.S. heated pavement was implemented for the first time on a bridge deck in Oregon (Thurston et al., 1985), and since that time HHPS have been widely-used worldwide (Pan et al., 2015). However, before HHPS would be considered for airport implementation, it is necessary to evaluate the prospective energy and cost effects of such systems, and the literature in this area does not reflect much research attention given to these aspects to date (Pan et al., 2015).

In view of this scarcity, the main goal of this paper is to assess the economic feasibility of HHPS for apron applications in commercial airports. To achieve this objective, the potential benefits of HHPS implemented using Portland Cement Concrete (PCC) pavements were examined for two commercial airports, one a large-hub facility and the other a small-hub facility. The findings of this paper can help readers achieve better understanding of the different costs and benefits associated with snow clearing using HHPS with natural gas as its primary energy source. The methodology described herein can also be applied to other airports and used as a decision-making tool in evaluating potential adoption of this alternative technology.

Airport Site Selection

It is naturally to be expected that commercial airports in areas that experience a large snowfall would benefit most from HPS installation, so airports with an average yearly snowfall more than 90 cm per winter and ice/snow removal operations averaging requiring a minimum of 20 days per winter were identified as candidates for this study. Among the candidates, and particularly since airports in close geographical proximity were preferred for facilitatation of site visits, the following two commercial airports were selected for this analysis:

a) Minneapolis/Saint Paul International Airport (MSP), Minneapolis, MN, a large hub airport experiencing nearly 17 million enplanements in 2017 (1% of total U.S. enplanements) (Schaufele et al., 2017). MSP has one airfield with four runways, all operational during winter storms. MSP was the 17th busiest airport in the U.S. in 2017 based on its volume of air traffic (BTS, 2017a).

b) Des Moines International Airport (DSM), Des Moines, IA, is a small-hub airport experiencing marginally more than 1.1 million enplanements in 2017 (Schaufele et al., 2017) and daily supporting nearly 220 daily aircraft operations. DSM has two runways, both operational during winter season.

Economic Analysis Approach

Deterministic economic analysis approach is a decision-making method that uses discrete values and produces a single-value output. The important factor in such analysis is benefit-cost ratio (BCR), "*calculated by dividing the net benefits by net costs*" (FHWA Pavement Division, 1998). If the BCR of a potential project is greater than one, the investment on the project is considered to be an economically viable choice for investors (FHWA Pavement Division, 1998). "*The outcome of a deterministic LCBCA depends on numerous estimates, forecasts, assumptions, and approximations, with each factor having potential for introducing error into the results*"

(Gransberg and Kelly, 2008), and decision-makers must know the effects of such errors on the outcome of the LCBCA (Ali Nahvi, 2017; Asiedu and Gu, 1998; Daghighi et al., 2017; Gransberg and Kelly, 2008; Gransberg and Scheepbouwer, 2010; Nahvi, 2017; Nahvi et al., 2018; Sri, 2017). The issues listed, associated with a deterministic economic analysis approach, can often be resolved using stochastic life-cycle cost model development (Daghighi and Nahvi, 2014; Touran and Wiser, 1992).

The Stochastic Economic Analysis Model

The stochastic life-cycle assessment method, often used for sustainable infrastructure management (Banar and Özdemir, 2015; Batioja-alvarez et al., 2018; Ceylan et al., 2018; Gransberg and Scheepbouwer, 2010; Kucukvar and Tatari, 2012; Noshadravan et al., 2013; O'Born, 2018; Pittenger et al., 2012), was used in this paper to determine HHPS financial viability, as described in the following section. "*The stochastic LCBCA approach uses Monte Carlo Simulation (MCS) and allows input variables to vary through their probability distributions based on recent historical and regional changes*" (Kucukvar et al., 2014). Figure 3-2 illustrates the steps followed in this study for forming such a stochastic LCBCA framework. Major costs and benefits with use of HHPS were listed based on discussions with FAA officials and DSM and MSP airport mangers. Different costs and benefits of using HHPS were calculated, followed by Monte Carlo Simulation (MCS) to evaluate how changes in values of certain variables impact the benefit-cost ratio under a given set of assumptions. "*MCS supports quantification of the range of possible BCR values by performing sensitivity analysis to identify the individual impact of each input variable on the overall BCR model*" (Touran and Wiser, 1992), and BCR results were displayed using a probability density graph.

To estimate costs/ benefits related to HHPS, different types of data were gathered. Specifically, data related to the number of operations, the frequency of delays, and each delay's duration, along with capital, operational, and maintenance costs of traditional methods, were collected for economic analysis. Since direct data collection from each airport related to the frequency of delays occurring at each airport and their causes was not achievable due to unavailability of such data, most of the required delay-related data were obtained from publicly-available sources, i.e., the Bureau of Transportation Statistics (BTS) and the Research and Innovative Technology Administration, consistent with the BTS definition: *"A flight is considered delayed if it arrives 15 or more minutes later than its scheduled time"* (BTS, 2017b). While there can be many reasons for flight delays, on average for all airports, the fraction of weather-related delays occurring at a point of departure, is approximately 5% of all delays. While such delays are usually caused by extreme weather such as tornadoes, blizzards, or hurricanes (Bureau of Transportation Statistics, 2017), since most weather-related flight delays during winter are due to snowfall (WeatherBill, 2017), forthe purposes of this study delays relative to ice and snow removal operations can be assumed to be approximately 3% of total operations (Anand et al., 2017). The percentage of delays related to snow/ice removal was also added as one of the inputs to the stochastic economic analysis model. After discussions with the airport managers, costs and benefits were also assumed to vary as a function of the area considered.

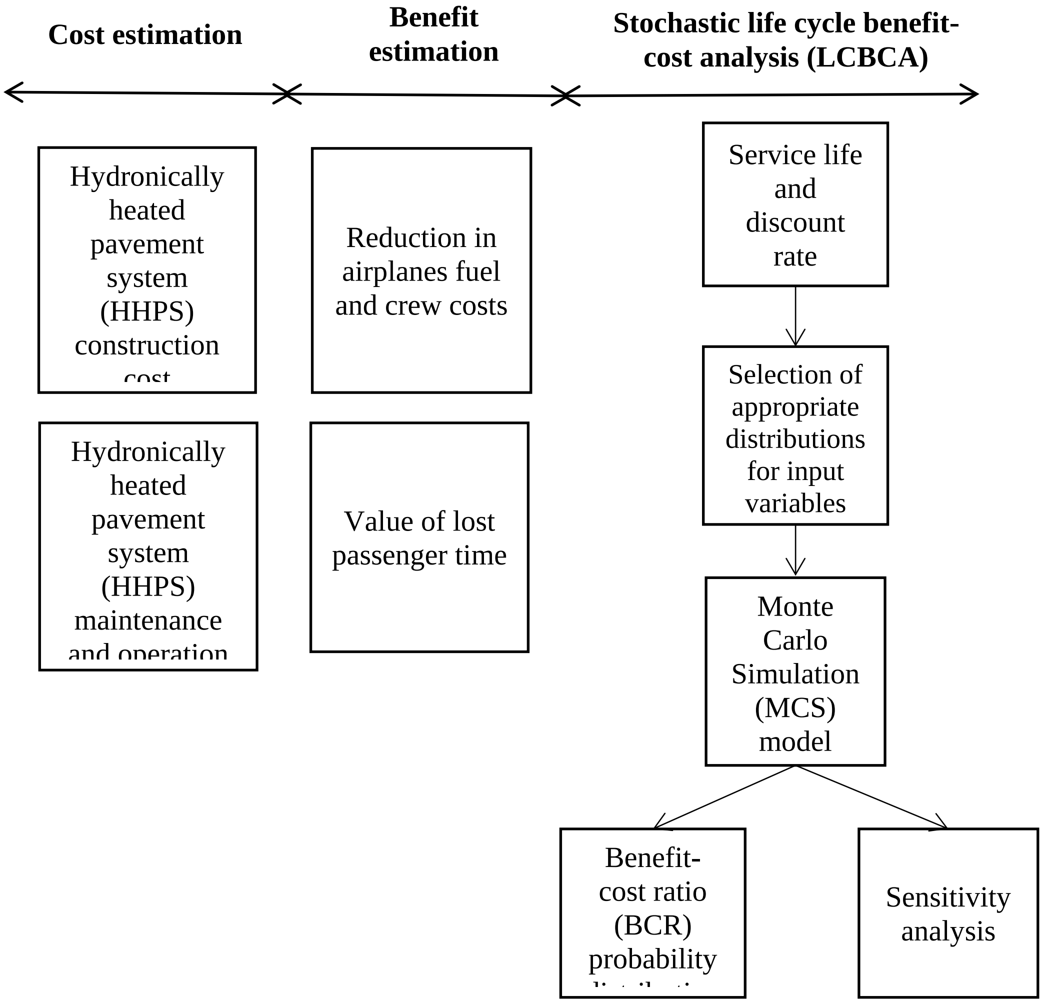


Figure 3-2 Methodology followed in the study to conduct stochastic economic analysis

Cost estimation

This section describes costs related to removal of snow using HHPS and is specifically related to cost estimation. The costs considered included initial, operational, and maintenance costs.

Capital Cost

Initial construction cost is one of the main components of LCBCA (FHWA Pavement Division, 1998). The initial construction costs of HHPS were obtained from project bid tabs provided by Midwestern HHPS contractors. Bid data provide a simple, reliable, and quick source for estimating unit costs (Tehrani, 2016). The data set used in this analysis contained bid records obtained over the previous two-year period (September 2015 to December 2017). Figure 3.3 shows how unit costs of various HHPS projects were distributed during this period, and also shows the unit cost of HHPS implementations both at airfields and at other locations (hospitals, rest areas, sidewalks, etc.). To determine significant differences between unit costs of projects at airfields and those at other HHPS installations, projection of t-tests can be useful statistical tools for examining differences between two population means. A statistical t-test was conducted using a selected confidence level of $(1 - \alpha) = 0.05$, meaning that a result is not considered significant if $p < 0.05$. All the unit cost values were plugged into the MCS model to capture variations in installation costs arising from different concrete thicknesses, location factors, project specifications, and heating system types.

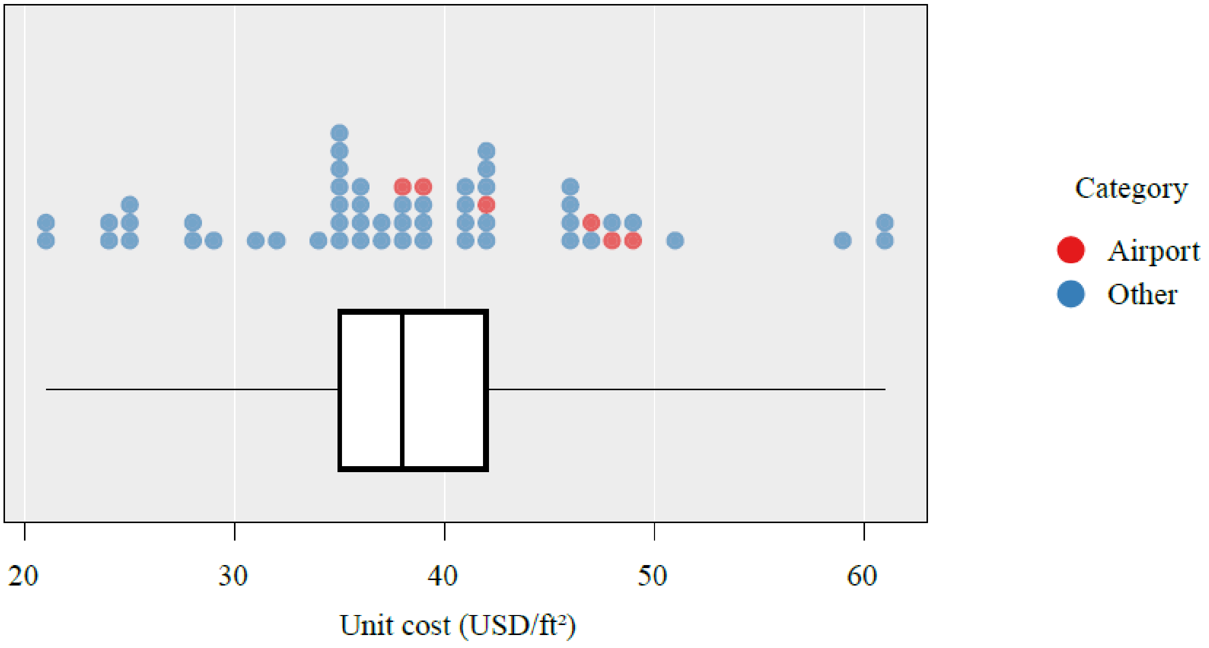


Figure 3-3 Construction unit cost for 58 hydronically-heated pavement (HHPS) projects (provided by heated pavement contractors in Midwest)

Maintenance

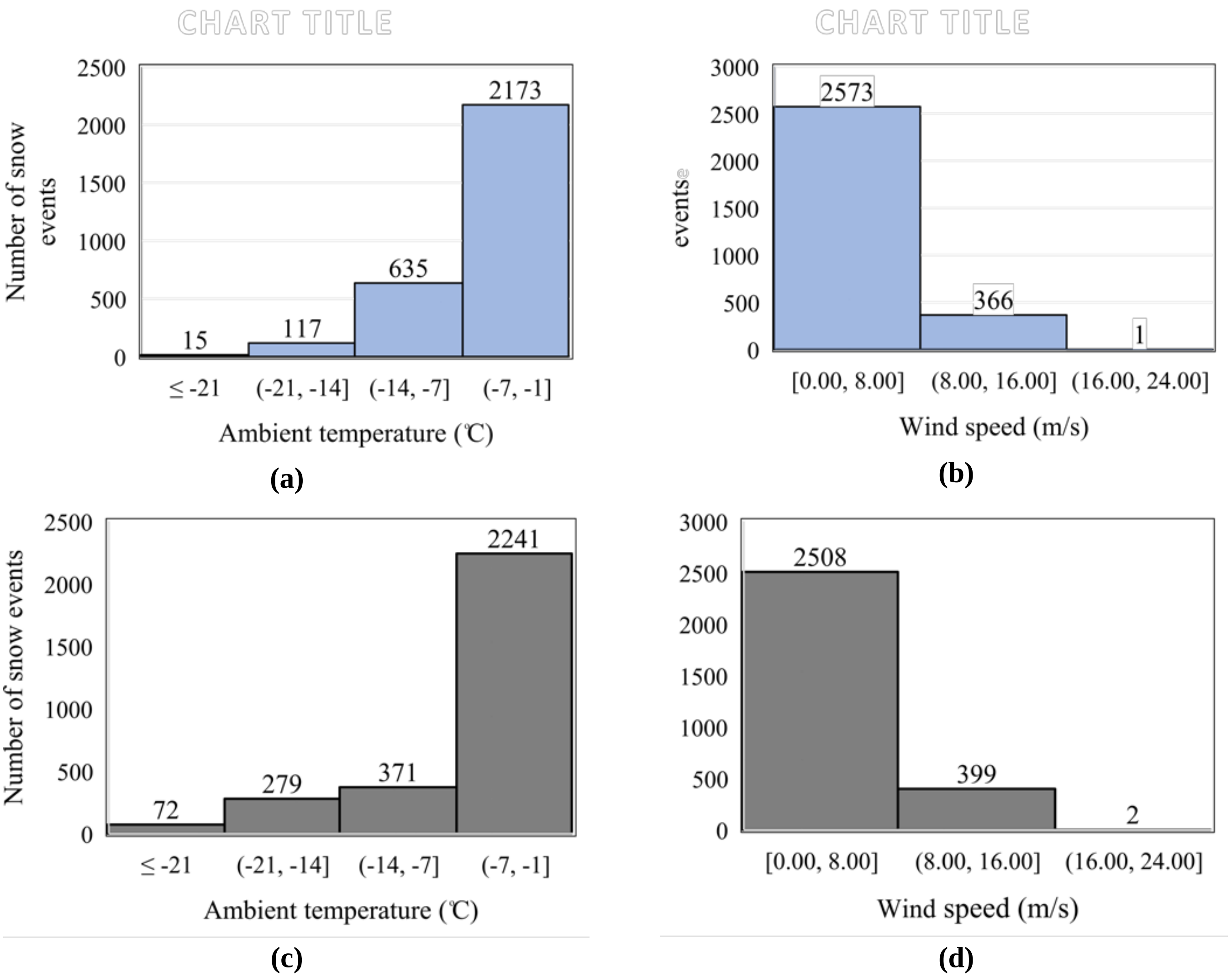
Based on information obtained from DSM airport managers, costs of maintaining large-scale hydronic airfield heated pavement system can be assumed to be about 1% of its construction cost. Note that, because historical records regarding costs associated with maintenance of HHPS subject matter were unavailable, expert opinions (i.e., from DSM maintenance managers) were used to quantify maintenance costs of HHPS. "*Expert Judgement techniques are useful for quantifying models in situations in which, because of either cost, technical difficulties, or the uniqueness of the situation, it has been impossible to make enough observations to quantify the model with real data*" (Bedford et al., 2016).

Operational costs

With respect to operational costs, since the assumption was made that a HHPS would be operated using automatic controllers and switching equipment, no labor costs would be required, so operational costs were assumed to be only the cost of energy (i.e., natural gas) essential to warm the anti-freezing liquid flowing through the pipes and the cost of electrical power required by the controlling system. To measure the amount of energy (i.e., volume of natural gas needed to melt ice and snow), the design heat load was first estimated, as described in the following section.

HHPS Energy Consumption

There have been several previous studies on energy modeling of HHPS. Xu and Tan studied the energy demand of HHPS under different weather scenarios, including extreme weather conditions (Xu and Tan, 2015) consistent with other studies on HHPS energy consumption (Xu et al., 2018). These scenarios were established by selecting different combinations of ambient temperatures ranging between -6 and -30°C, a wind-speed range of 4 to 8 m/s, and snowfall rates ranging from 0.2 to 0.8 mm/h. In seeking to use results from the aforementioned studies for the current paper, the weather conditions at the case study locations were investigated using temperature, wind speed, and snowfall rate recordings obtained from automated surface-observing systems during snow events at DSM and MSP between 1987 and 2017 (ASOS, 2018); there were 2,940 and 5,567 data points during snow events at DSM and MSP, respectively, over this period. As shown in Figure 3-4, all the temperature values, 88% of the wind-speed readings, and 85% of the snowfall rate values during the investigated snow events at DSM fell into similar ranges of weather conditions as those studied by Xu and Tan (2015). Similarly, in the case of MSP, all ambient temperatures, 93% of wind speeds, and 89% of snowfall rates were in these range. Since most of the weather condition recordings during snow events for both DSM and MSP had been previously considered in Xu and Tan's study, their estimates of the distribution of total energy consumption of HHPS were used in this study.



(a) **(b)**

(c) **(d)**

Figure 3-4 Histogram of climatic conditions during snow events from 1987 to 2017 for case studies (ASOS, 2018): (a) Ambient temperature (℃) in DSM, (b) Wind speed (m/s) in DSM, (c) Ambient temperature (℃) in MSP, (d) Wind speed (m/s) in MSP, (e) Snow fall rate

Idling time, defined as the time needed for a system to increase the pavement surface temperature to the melting point of 0.5℃ (ASHRAE, 2001), was used as a criteria for evaluating a system's capability for melting snow and preventing snow accumulation under different weather conditions. The shorter the idling time, the higher the heating capacity of the boiler for heating the fluid running through the embedded pipes. Among all weather parameters, ambient temperature has the strongest effect on idling time (Xu and Tan, 2015). Since idling time provides a reliable picture of system performance, it has been taken as the main parameter in the design of HHPS. According to temperature recordings for DSM and MSP, if boilder heating capacities of 0.6, 0.9, 1.2, 1.5 and 1.8 kW/m^2 were considered, the worst-case scenario for idling time would be 150 minutes (Xu and Tan, 2015), and this conservative assumption was used in this paper in performing the operation cost analysis. Four possible scenarios for system performance were developed based on ambient temperatures lying within the ranges listed in Table 3-1. This study assumed that, for each snow event, the system would start 150 minutes before that event and run continuously until the end of the day.

Table 3-1 Assumptions and results of energy consumption assessment

Scenario	**Ambient temperature** (All temperatures for all snow events are within these bounds)	**Heating capacity of boiler required (kW/m^2)**	**Required Natural Gas (ft^3/m^2)**	**Probability in DSM**	**Probability in MSP**
A	> -6˚C	0.6	50	74%	67%
B	< -6˚C > -14˚C	1.2	98	22%	25%
C	< -14˚C > -22˚C	1.8	147	4%	8%
D	<-22˚C	System is not functional	0	1%	1%

If the ambient temperature was below -22˚C, the idling time would be more than 150 minutes (Xu and Tan, 2015). As shown in Table 1, for one percent of all snow events, the ambient temperature would be below -22˚C, the idling time would be greater than 150 minutes, and the HHPS alone would not be practical for melting ice and snow, so auxiliary snow removal machinery and crew along with the HHPS would be necessary to adequately remove airfield ice and snow under such extreme conditions. Annual energy consumption costs can be calculated using Equation 1.

$$C = E_m \times A \times N_s \times e \times E_p \tag{1}$$

where C is annual energy consumption cost, A is HHPS paved area (m^2), E_m is average energy use (kWh/m^2), N_s is the number of snow events, e is the efficiency factor (0.85) (Cleaver Brooks, 2010; lo Storto, 2018), and E_p is price of natural gas (USD/kWh), (values obtained from U.S EIA, 2018). Since there are many uncertainties associated with annual energy consumption (i.e., E_m, N_s, $and\ E_p$), considering a discrete input for annual energy consumption cost in the economic analysis can introduce bias into the results. Issues associated with a deterministic annual energy consumption cost model (Eq. 1), including volatility of underlying commodity prices, was addressed by developing a MCS-based analysis whose results are presented in the Results and Discussion sections.

Estimation of Benefits for HHPS

In considering HHPS benefits, the effects of time lost from using conventional technologies during snow removal operations were investigated and projected into the financial values. The main anticipated benefits associated with HHPS field implantation studied in this paper were reduced passenger delay and reduced plane operating delay costs. The following sections describe the estimation of each such aspect.

Value of lost passenger time

The main factor to be accounted for is the collective lost time value by passengers who experience flight postponement, and a reduction in the associated costs would represent a major benefit of HHPS. To put the potential of this benefit into perspective, (Ball et al., 2010) estimated that, in 2007, domestic passenger flight delay costs were $16.7 billion (in 2007 dollars) imposed on the

U.S. economy. Note that passenger delay costs represent only indirect costs because aircraft operators in general offer no form of compensation (e.g., free meals or discount on accommodation) for snow-related flight postponement. Passenger costs due to delays were calculated according to air-traffic demand, with the number flights each day, the seats available on each plane, and a load factor estimate used to adjust the demand. “*Load factor is a measure of the use of aircraft capacity that revenue passenger-miles as a proportion of available seat-miles (ASMs)*” (BTS, 2017c). In 2017, the average load factor for U.S domestic air transports was 84.4 % (BTS, 2017c).

Also, since flight demand capacity is not constant over time and is on average anticipated to grow every year, the average passenger volume growth rate was considered to be 3.4% per year for the next twenty years, in line with an FAA prediction (Schaufele et al., 2017).

The value of lost passenger time is also related to trip purpose, so passengers were categorized into two groups: those traveling for personal/leisure purposes and those flying for business (Belenky, 2011). Table 3-2 shows the values of time per trip purpose considered in this study.

Table 3-2 Values of time per trip purpose on a delayed flight

ςαλυε οφ τιμε (περ ηουρ)	Χοστ (ΥΣ/ ηουρ)	Passengers percentage based on trip purpose (%)	Number of passengers in a flight
Personal/leisure	36.1	59.6	74.5
Βυσινεσσ	63.2	40.4	50.5

Passenger delay costs were estimated using Eqs. *(2)* and *(3)*.

$$T_d = N_d \times P_s \times P_g \times A_d \times 120 \times 99\% \qquad (2)$$

where T_d *is* total lost time per winter season, N_d is number of aircraft operations each day, P_g is the passenger growth rate, P_s is the number of delays related to snow/ice removal operation, and

A_d is the duration of each delay (hours).; the value 120 value reflects an average of 30 days per month multiplied by 4 months per winter season. For one percent of the scenarios, because use of HHPS alone is occasionally not a practical approach for ice and snow melting (as mentioned in the HHPS Energy Consumption section), benefits were estimated for 99% of the snow events.

$$A_m = T_s \times L_f \times P_p \times T_p \times V_t \times 99\% \qquad (3)$$

where A_m is the yearly monetary value of traveler time (USD), L_f is the load factor, T_s is the total number of seats in each plane, P_p is passenger percentage based on trip purpose, and V_t is monetary value of time consistent with the trip purpose. Similar to the reduced passenger delay costs, benefits were estimated for 99% of the snow events.

Reduction in aircraft operating delay costs

With respect to aircraft operating delay costs, the key factors contributing to the anticipated reduction in cost of using HHPS are reduced aircraft fuel wastage and reduced extra crew working hours. For aircraft operating delay costs, the number of delayed air travels was estimated using the same method as for estimating value of lost passenger time. With respect to the particular points at which such delays occur, there are three types of aircraft delays: mid-air, gate, and ground delays. Mid-air delays will result in the highest amount of fuel wastage; gate and ground delays will be related to idling fuel wastage only. The cost of mid-air delays is approximately $4,449/h, and the costs of ground and gate delays are $2,169/h and $1,457/h, respectively (Mcgormley et al., 2016) (adjusted for 2017 values). Each delay category would contribute a different percentage to the total delays and therefore incur different costs. Because such information was unavailable, the assumption was made that all types of postponements would occur in the same proportion, yielding an average value of a $2,850/h cost experienced by airlines during ice/snow related delays. The yearly (for the four months considered) cost to airlines due to snow removal operation can then be calculated by multiplying this value by the total number of operations during the winter months. The annual operation growth rate for subsequent years is also included in these calculations.

Service Life and Discount Rate

FAA economic analysis manual (FAA, 1999) for major airport infrastructure projects suggests adoption of a 20-year economic life span beyond completion of construction. In addition, for capturing discount-rate fluctuations in the economic analysis and evaluating discount-rate sensitivity with respect to the BCR, the previous twenty-year (1997 to 2017) discount rate data from the Federal Reserve (Federal Rserve, 2018) was obtained, fitted to the appropriate probability distribution, and introduced into the model.

Selection of Appropriate Distribution of Variables

A range of different types of data were collected to estimate benefits and costs associated with use of HHPS. Specifically, these include data related to the number of operations, the number of delays, and the duration of each delay, along with capital, operational, and maintenance costs of traditional methods. Table 3 includes a summary of the data utilized for ECON cost/benefit estimations. The values of some of the inputs were common to both case studies, while the values of some variables (e.g., the duration of each delay, the ambient temperature, and the amount of snowfall in one hour) differed.

Table 3-3 Data collection summary for HHPS benefits/costs estimation for studied airport

Category	**Benefit/cost by shifting from CSRS to HHPS**	**Item**	**Source**
Benefits	Value of lost passenger time	Annual number of delays	(BTS, 2017a)
		Total delay hours in winters	(BTS, 2017a)
		Load factor	(Schaufele et al., 2017)
		Percentage of passengers traveling for business	(Belenky, 2011)
		Value of time for leisure	(Belenky, 2011)
		Value of time for business	(Belenky, 2011)
	Reduction in fuel consumption and crew costs	Mid-air delays	(Mcgormley et al., 2016)
		Ground delays	(Mcgormley et al., 2016)
		Gate delays	(Mcgormley et al., 2016)
		Total delay hours in winters	(BTS, 2017a)
Costs	HHPS Operational Costs	Construction cost	Discussion with contactors (Figure 3-2)
		Price of commercial natural gas	(U.S. Energy Information Administration, 2018)
		Annual number of snow events	(NOAA, 2017)

"*Determining the appropriate probability distribution for each input variable is an important step in the stochastic LCBCA approach*" (Anand et al., 2017). A maximum likelihood method was used to fit the variables to a distribution, and the best fit distribution was chosen based on a chi-squared goodness-of-fit test (Pearson, 1992). For percentage of weather-related delays associated with limited sample data, a triangular distribution, appropriate for variables with limited data (Gransberg and Kelly, 2008), was used. The variables obtained using historical data and the best fitted distributions for the input variables are shown in Table 3-4. To represent the amount of variation in the input variables, standard deviations are also reported in the Table 4.

Table 3-4 Variables distributions for Monte Carlo simulation (MCS)

Common variables to both DSM and MSP		
Input variable	**Distribution**	**Description**
E_c - Electricity use (W/m^2)	Discrete	
Discount rate (%)	Pareto	Std = 1.1 α = 3.1
T_p - Trip purpose (-)	Discrete	

Uncommon variables				
Input variable	**Distribution**		**Description**	
	DSM	MSP	DSM	MSP
E_p - Gas price (USD)	Triangular	Triangular	{3.1,3.8,14.2}	{5.3,6.7,9.9}
N_s – Number of snow events	Normal	Normal	μ= 16 Std = 7	μ= 25 Std = 9
N_d - Number of operations in each day (-)	Normal	Normal	μ= 198 Std = 23.3	μ= 605 Std = 47.9
A_d - Duration of each delay (hours)	Normal	Logistic	μ=0.78 Std = 0.21	μ=0.95 Std = 0.36

Results and Discussion

A MCS was conducted to determine a probabilistic energy consumption cost and LCBCA for each case study. Using Equation 1 and the distributions shown in Figure 3-5 cumulative probability curves of the energy consumption costs of DSM and MSP were estimated and are shown in Table 3-5.

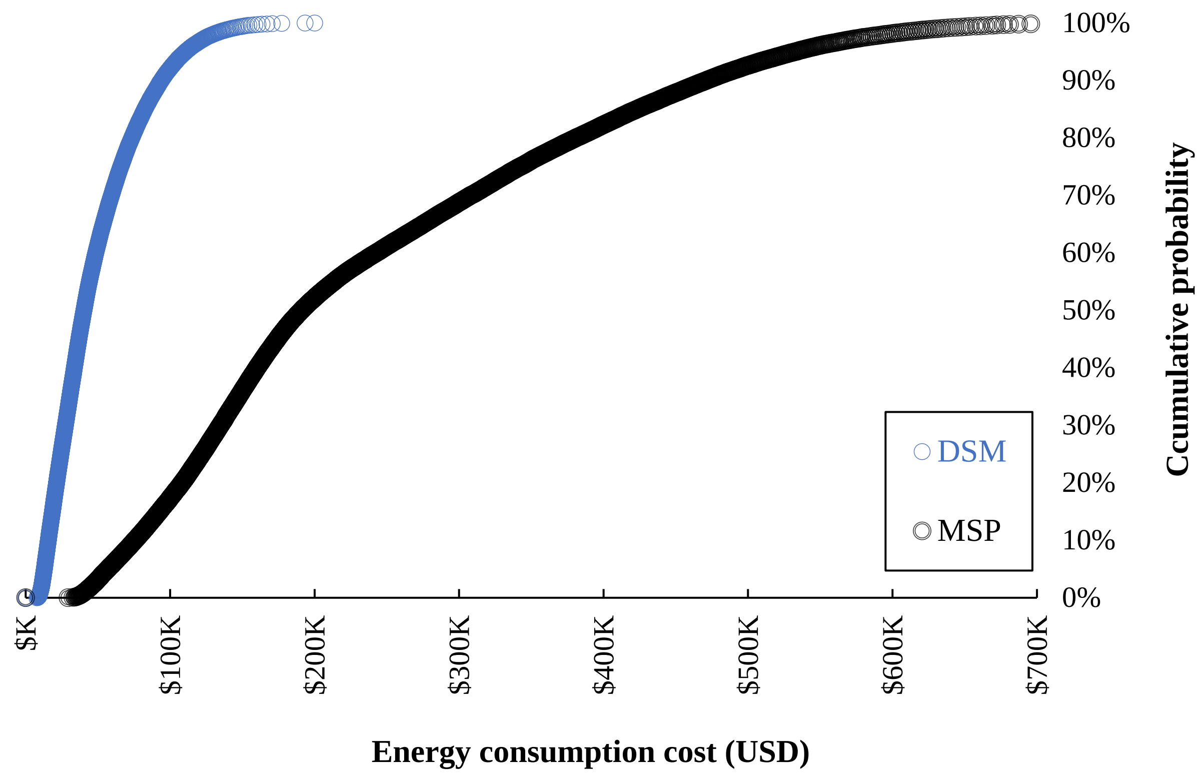


Figure 3-5 Energy consumption cost (USD) for an apron area

As shown in Figure 3-5, the annual median energy consumption costs of HHPS at MSP) is almost six times larger than that for DSM. This difference is mostly related to cumulative apron area size in MSP, almost three times bigger than that of DSM. To perform the same base comparison, the median energy consumption per square meter was calculated by dividing median energy consumption costs by size of apron area, yielding a median energy consumption per square meter for MSP of 4.2 USD/m^2, 1.7 times larger than for DSM (2.4 USD/m^2), with the main cause for this difference related to the greater number of snow events at MSP each year. Another simulation was conducted to measure LCBCA for each case study. Table 3-5 describes the probability density function for the BCR at DSM and MSP, reflecting a possibility that, when implementing HHPS, benefits would compensate for costs in all possible scenarios in DSM and MSP, with the median value of BCR in the case of MSP case almost 60 % higher than for DSM.

Table 3-5 BCR summary statistics and likelihood of occurrence.

BCR Summary Statistics			**Likelihood of Occurrence**		
	DSM	**MSP**		**DSM**	**MSP**
Minimum	1.08	2.02	**95%**	2.49	4.50
Maximum	2.84	5.09	**85%**	2.30	4.18
Mean	1.81	3.13	**75%**	2.07	3.77
Std. Dev	0.40	0.67	**10%**	1.21	2.37
Median	1.71	3.13	**5%**	1.19	2.27

As mentioned in the discussion of the economic analysis approach, another output produced by running MCS is stochastic sensitivity analysis to identify the influence of each input variable on the overall benefit-cost ratio. Such a sensitivity analysis was conducted to test the effects of changes in different parameters with respect to the final decision (Figure 3-6)

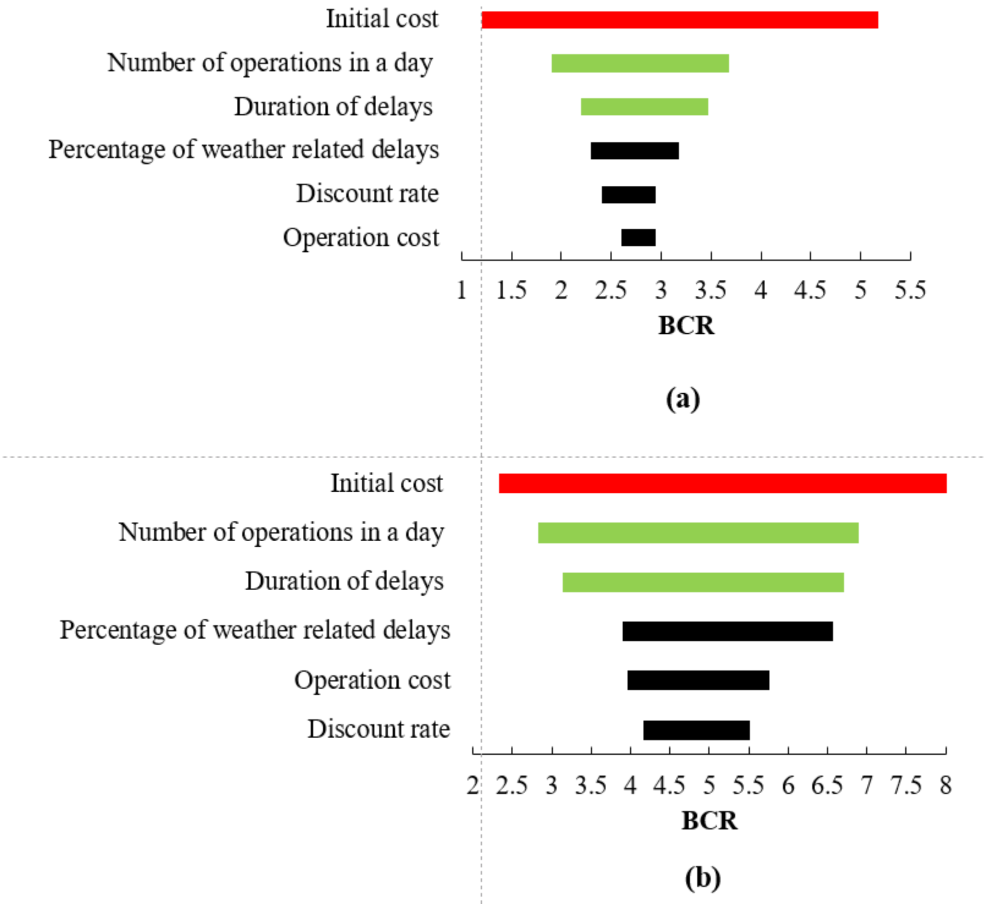


Figure 3-6 Sensitivity analysis results (tornado graph); (a) DSM, (b) MSP

BCR appears to be sensitive to initial installation costs independent of airport size. In fact, as shown in Figure 3-6, capital cost is the only variable that by itself drove the BCR to a value near 1.0 for the worst-case scenario related to the DSM case. In addition, while larger air-transportation terminals such as MSP seem to be even more sensitive to initial costs, in the case of MSP BCR remains above 2.0 for the whole range of initial costs considered in the analysis. At the same time, the findings suggest that the BCR of such large airports is also sensitive to both the number of operations and the delay durations. As can be seen in Figure 3-6, since the number of operations and delay durations seem to be among the major factors that drive the benefits of the HHPS for MSP, it is reasonable to conclude that the size of the airport in terms of the number of airplane operations would have a considerable impact on the BCR. Aside from a direct increase in benefits expected to result from a growth in the number of operations, it is also possible that economies of scale, with cost per unit of output decreasing with increasing scale, could impact results of the economic analysis, although such factors were not directly evaluated in this study.

Conclusion and Recommendation

This study quantified costs and benefits associated with HHPS. The methodology described herein and the findings of this analysis can assist commercial airport managers in making better-informed decisions in selecting a suitable option among alternative adverse winter weather operational strategies. This paper also proposes a method for estimating energy consumption and operational costs of HHPS for large areas such as airport aprons.

The following key recommendations based on this study’s key findings are:

- From a cost-benefit perspective, while the use of HHPS is a potentially viable option for combatting airport snow and/or ice conditions, the HHPS cost-benefit ratio for an airport mostly depends on several site-specific airport characteristics, including the number of airplane operations and the HHPS implementation area, so the cost-benefit results of utilizing HHPS should be evaluated on a case-by-case basis.

- Because all airport aprons are not used at all times, the boiler capacity could also be designed to reduce initial costs by time-sharing its use among different areas. It is expected that future advancements in HHPS construction practices and technology would further decrease initial and operational capital costs. Future research can explore the potential of such technologies and associated and construction practices.
- Conceptually, HHPS implementation sufficient for snow/ice removal might be used in maintaining regular airport operations only in portions of apron areas. If site investigations and experimental studies can demonstrate that heating only a portion of the total apron area could help in reducing flight delays, the use of HHPS might prove to be considerably more cost-beneficial than originally estimated. This finding is especially important for smaller hub airports such as DSM.
- The methodology developed in this paper could be extended to examining the economic viability of other similar technologies, such as electrically-conductive asphalt/PCC concrete (Arabzadeh et al., 2018; Sassani et al., 2018) blended with superhydrophobic materials (Nahvi et al., 2017).

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CHAPTER 4. ECONOMICS OF ELECTRICALLY CONDUCTIVE HEATED AIRFIELD PAVEMENTS

This paper will be submitted in Journal of Cold Regions Engineering

Abstract

Conventional snow removal strategies add direct and indirect expenses to the U.S. economy through the profit lost due to passenger delays, pavement durability issues, and contaminating the water runoff. Electrically conductive concrete heated pavement systems (ECON HPS) are new resilient technologies for airfield snow removal operations. In this study, economic performance of ECON HPS is investigated through Monte Carlo simulation-based Life Cycle Cost Benefit Analysis (LCBCA) for the largest commercial airports in the US that experience harsh winter events. To this end, states that experience average annual snowfall of more than 635 mm (25 inches) were identified; costs and benefits associated with ECON HPS placement were determined for aforementioned case studies based on experiences obtained from the first full-scale ECON HPS implementation at Des Moines International Airport (DSM). The result of the analysis showed that Chicago O'Hare International Airport (ORD) would benefit the most from ECON HPS installation. In addition, for three case studies (i.e. Salt Lake City International Airport (SLC) and Denver International Airport (DEN) along with ORD), the benefit cost ratio (BCR) was bigger than one in all of the possible scenarios based on the set of assumptions and data used in this study. Finally, a stochastic sensitivity analysis was conducted to determine variables that have significant impacts on the overall economic performance of ECON HPS. The result of this analysis indicate that the duration of delays and number of airplane operations along with construction costs have the most significant impact on BCR.

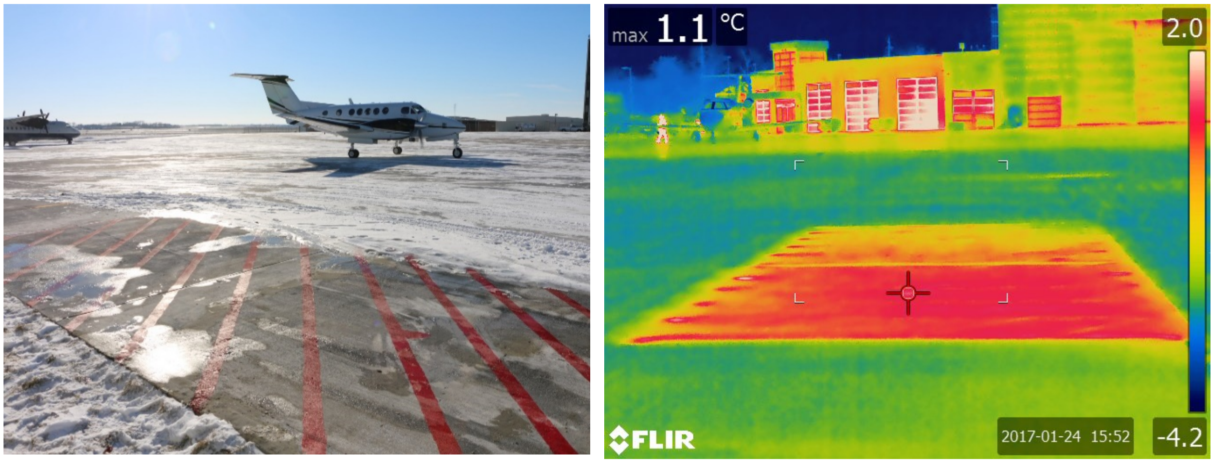
Keywords: Resilient airfield pavement; Electrically conductive concrete Hated pavement; Snow and ice removal; Stochastic life cycle benefit cost analysis; Monte Carlo simulation.

Introduction

Flight delays are a widespread challenge which impact the economy of every country, including the United States. One flight delay can generate a network delay, affecting different flights, and even a small delay can result in something more serious in the network, which might even lead to flight cancellations (Ferguson et al. 2013, Fleurquin et al. 2013). Also, all those delays generate unforeseen costs to airports, airlines, and passengers (Janic 2015). It is estimated that transportation delays cost approximately 32.9 billion dollars 2007; in the same year it was predicted this translated to a nearly 4 billion dollar reduction in the U.S. gross domestic product (Ball et al. 2010). Delays could be generated by different reasons, such as bad weather, accidents, natural disasters, and unpredictable aircraft failure (Janic 2015). About one-third of delayed flights from September 2016 to August 2017 in the U.S. were due to the harsh weather conditions in the winter season (U.S. Department of Transportation 2017).

The state of practice for removing ice and snow from paved surfaces at airports is typically through the use of snow removal machinary and treating the pavement surfaces with deicing and anti-icing chemicals (Baskas 2011). These methods are labor-intensive and time-consuming, and deicing chemicals can cause pavement long-term durability issues (Shi et al. 2009). Moreover, chemicals can contaminate the water runoff in the airports, which can negatively impact the environment (Shen et al. 2017). Therefore, a sustainable alternative method for removing ice and snow is needed, to help reduce transportation delays and consequently improve the U.S. economy.

Several recently-developed technologies have been recently studied to overcome the winter-related delays, which consist of super-hydrophobic coating techniques (Arabzadeh et al. 2016), phase-change materials (Farnam et al. 2015), hydronic heated pavement systems (HHPS) (Thurston et al. 1985), and electrical heated pavement systems (EHPS) (Abdualla et al. 2016). These technologies are developed to decrease the environmental effects of deicers and reduce flight delays, with an ultimate goal of saving time, energy and money. Electrically conductive concrete heated pavement systems (ECON HPS) are one type of EHPS, which apply an electric potential to pavement built with electrically conductive materials. Previously studied conductive materials which have been added to concrete include steel shavings (Tuan 2008), carbon powder (Farnam et al. 2015), and carbon fibers (Sassani et al. 2018). In November 2016, the first full-scale ECON HPS test slabs made using electrically-conductive carbon fibers were built in a U.S. airport at the general aviation apron of Des Moines International Airport (DSM) in Iowa (Figure 4-1).



(a) **(b)**

Figure 4-1 Electrically conductive concrete heated pavement system (ECON HPS) full scale demonstration at Des Moines International Airport; a) ECON HPS snow melting (photo taken January 2016); b) Thermal camera view (photo taken February 2017)

A large number of activities occur on airport aprons (e.g. oil-refueling operations, baggage handling, and etc.). In addition, the presence of machinery- and personnel-based activities impacts the ability to effectively utilize more traditional snow and ice removal operations in these locations (Merkert and Mangia 2012), making aprons a strong candidate for the use of ECON HPS. A previous study investigated and quantified the costs and benefits associated with the use of ECON HPS for apron pavement at DSM and Minneapolis-St. Paul International Airport, MN (MSP)

(Nahvi et al. 2018). This study investigated the economic performance of this technology through stochastic economic analysis. Due to the limitations associated with employing deterministic economic analysis approaches, a stochastic economic analysis method was used to investigate the economics of ECON HPS. The results of the aforementioned study indicated that benefits of using ECON HPS at DSM and MSP would be greater than its costs with a more than 70% and 90% probability, respectively (Nahvi et al. 2018). However, the economic performance of ECON HPS is limited to the investigation of the two airports in the aforementioned study. The main objective of this research is thus to investigate economic performance of ECON HPS at commercial airports that experience particularly harsh winters. Commercial airports that experience harsh winter events with frequent snowfalls would benefit the most from the use of ECON HPS. Therefore, eleven of the largest commercial airports in those states that experience an average annual snowfall of more than 635 mm (25 inches) were identified (Osborn 2017) for evaluation in this study as shown in Figure 4-2.

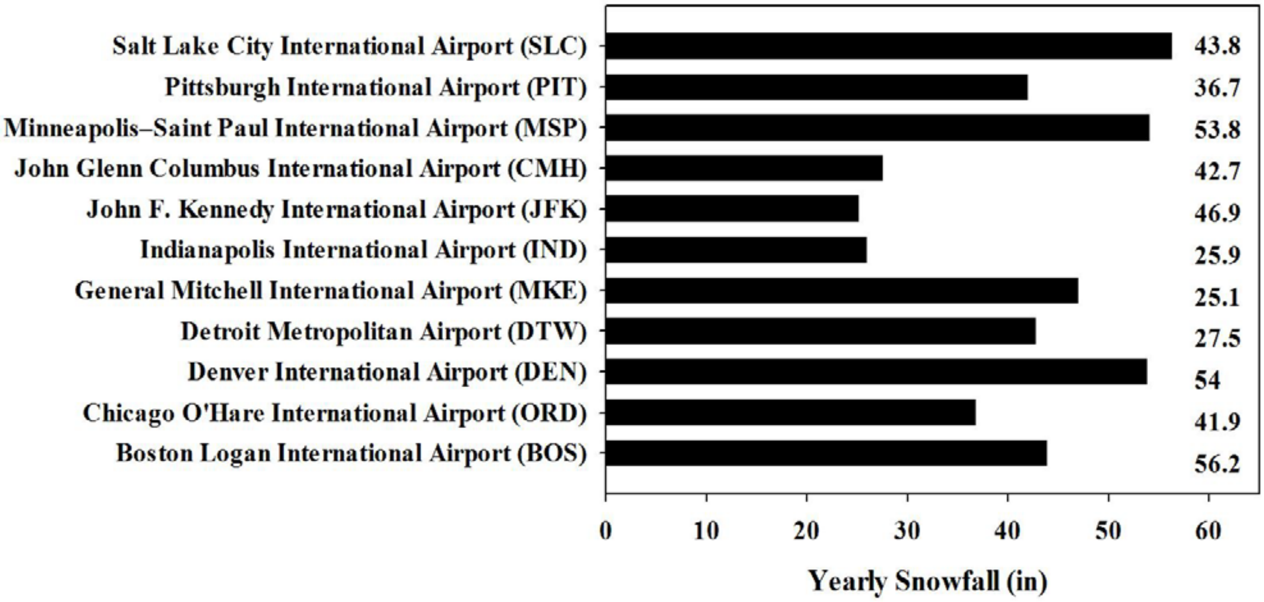


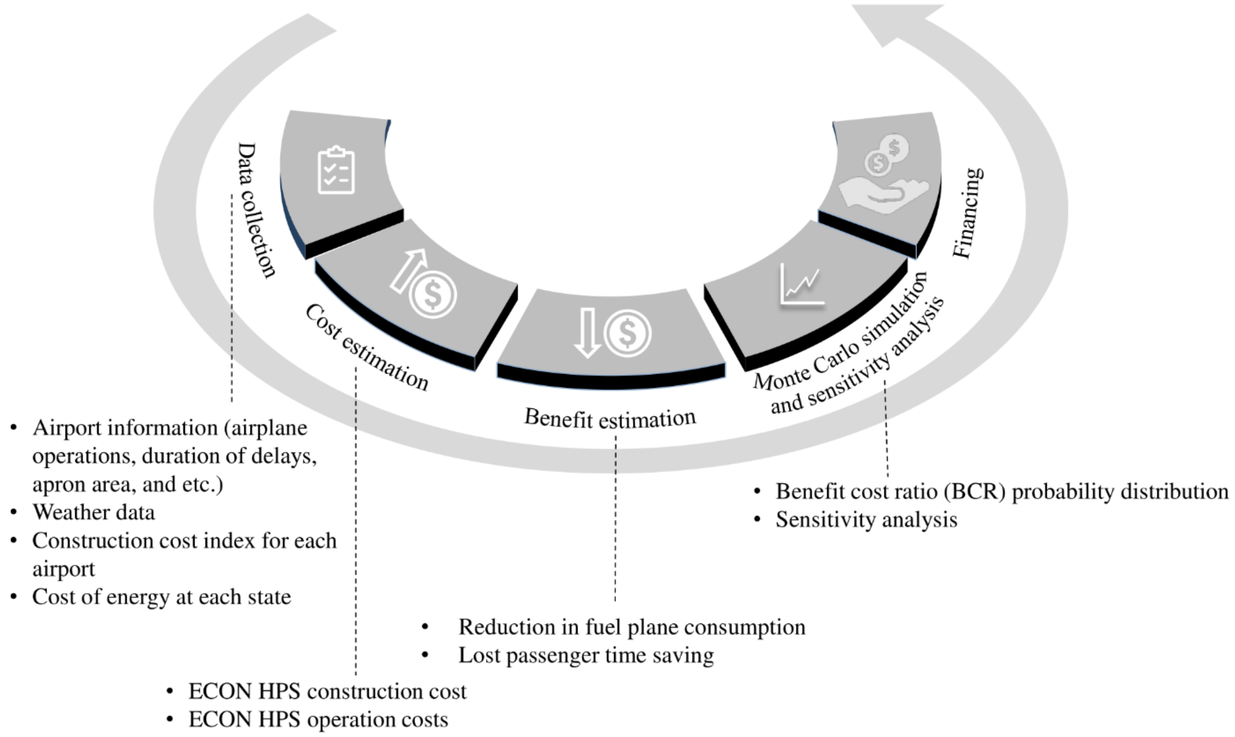
Figure 4-2 Yearly snowfalls in commercial airports studied

To this end, in this paper the methodology developed in the aforementioned study (Nahvi et al. 2018) was adapted to monetize ECON HPS benefits and estimate the construction and operation costs of such systems in the selected airports.

Another objective of this study is evaluating bank loans, the most popular financing source for construction projects (Qian and Yeung 2015), as financing option for ECON HPS large scale implementation. Note that, this paper does not aim to go into details about the different financing options available for financing a construction project but rather it aims at providing some insights about participation of financial institutions in implementing ECON HPS for apron areas. In the remainder of this paper the study approach, cost and benefit estimations, and economic analysis results are discussed.

Approach

The Life Cycle Benefit Costs Analysis (LCBCA) approach used in this study follows the methodology described in the FHWA life cycle costs analysis bulletin (FHWA Pavement Division 1998). This method involves using deterministic values for each variable which results in a single output value for benefit cost ratio. Outcomes of a deterministic LCBCA would depend on a range of assumptions; the impact of potential uncertainties associated with these assumptions and approximations must be known to make informed decisions (FHWA Pavement Division 1998). Therefore, similar to other studies on infrastructure life cycle cost analysis (Batioja-alvarez et al. 2018; Gransberg and Scheepbouwer 2010; Sritharan 2017), the stochastic economic analysis approach, recommended by FHWA, is used in this study. The research methodology is presented in Figure 4-3.



- Airport information (airplane operations, duration of delays, apron area, and etc.)
- Weather data
- Construction cost index for each airport
- Cost of energy at each state

- Benefit cost ratio (BCR) probability distribution
- Sensitivity analysis

- Reduction in fuel plane consumption
- Lost passenger time saving

- ECON HPS construction cost
- ECON HPS operation costs

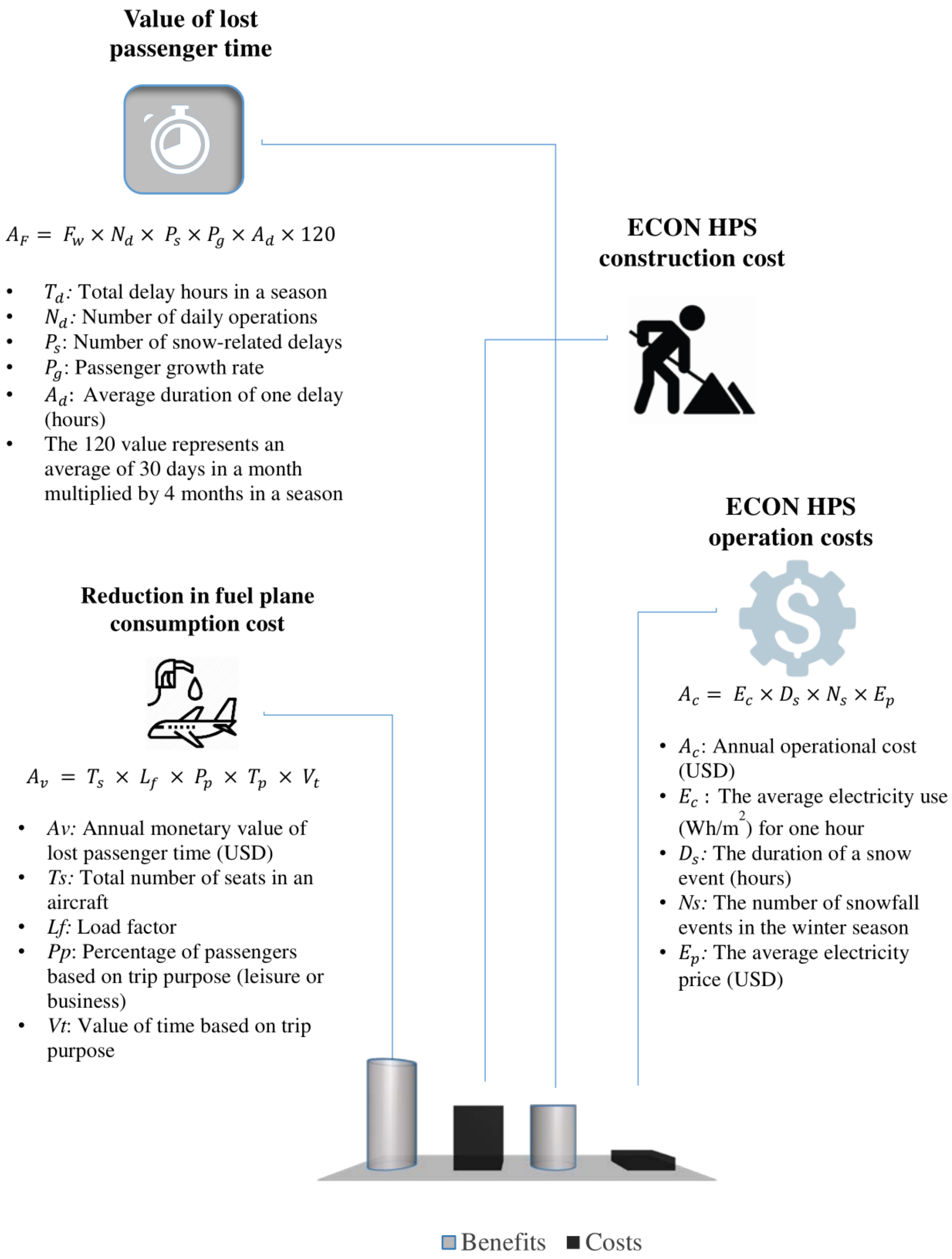
Figure 4-3 Research steps

As shown in Figure 4-3, to estimate the costs and benefits related to ECON HPS, different types of data were gathered such as cost of electricity for each state and data related to the following at each airport during last ten years: i) number of airplane operations, ii) number of delays, iii) duration of each delay, and iv) number of snow events. Then, Monte Carlo simulation (MCS) is used to measure the range of possible BCR values. A sensitivity analysis is then conducted to identify the individual impact of each input variable on the overall BCR model (for airports with highest and lowest median BCR value).

Costs and benefit estimations

Various advantages and disadvantages of ECON HPS were quantified using an approach used in Nahvi et.al. (Nahvi et al. 2018). Figure 4-4 summaries the approach used in the aforementioned study for ECON HPS benefit and costs estimations. The anticipated benefits after the installation of the ECON HPS include fewer passenger delays, minimized aircraft fuel waste, and enhanced safety. Passenger delay costs and reduction in fuel consumption can be calculated using equations obtained from the literature (Anand et al. 2017; Belenky 2011) and presented in Figure 4-4.

Note that the benefits of the ECON HPS use are not limited to the ones considered in this paper. The use of ECON HPS could directly impact flight delays on the airport where the material was applied. However, indirect impact, including benefits, might be noticed on different airports, and that is because both aircraft and crew may be scheduled for a sequence flight due to the existent air transport network. The benefit of this material application on the airline network can be considered in future studies.



Value of lost passenger time

$$A_F = F_w \times N_d \times P_s \times P_g \times A_d \times 120$$

- T_d: Total delay hours in a season
- N_d: Number of daily operations
- P_s: Number of snow-related delays
- P_g: Passenger growth rate
- A_d: Average duration of one delay (hours)
- The 120 value represents an average of 30 days in a month multiplied by 4 months in a season

Reduction in fuel plane consumption cost

$$A_v = T_s \times L_f \times P_p \times T_p \times V_t$$

- *Av:* Annual monetary value of lost passenger time (USD)
- *Ts:* Total number of seats in an aircraft
- *Lf:* Load factor
- *Pp*: Percentage of passengers based on trip purpose (leisure or business)
- *Vt*: Value of time based on trip purpose

ECON HPS construction cost

ECON HPS operation costs

$$A_c = E_c \times D_s \times N_s \times E_p$$

- A_c: Annual operational cost (USD)
- E_c : The average electricity use (Wh/m^2) for one hour
- D_s: The duration of a snow event (hours)
- *Ns:* The number of snowfall events in the winter season
- E_p: The average electricity price (USD)

Figure 4-4 Summary of calculation used to estimate benefits and costs associated with using ECON HPS (created based on (Nahvi et al. 2018)

Different types of data were collected to estimate benefits and costs associated with the use of ECON HPS. Specifically, these include data related to the number of operations, the number of delays, and the duration of each delay, along with capital, operational, and maintenance costs of traditional methods. Figure 4-5 exhibits data collection summary for ECON cost/benefit estimations.

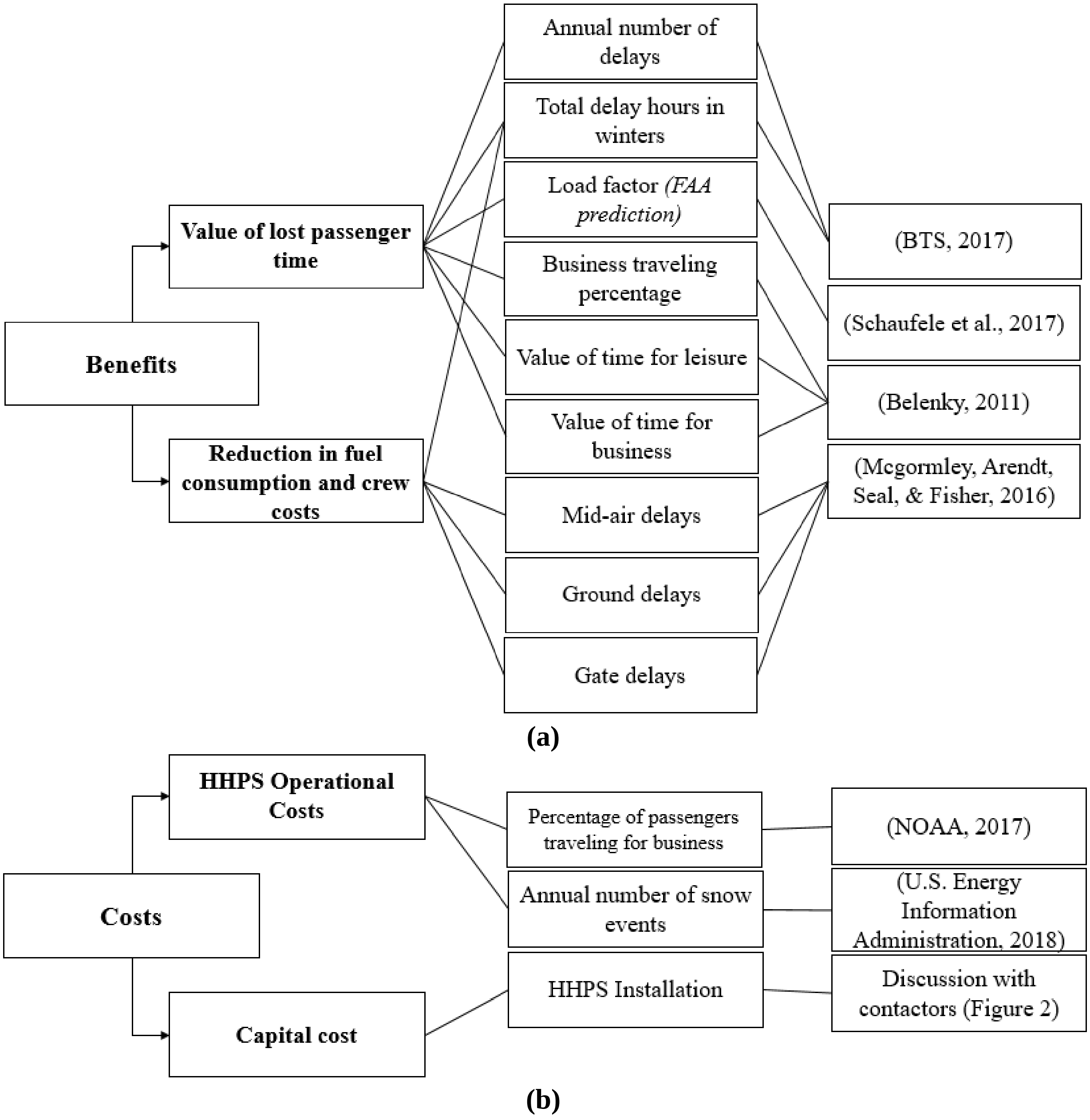


Figure 4-5 Summary of sources used for benefits/costs estimation

Initial construction cost of ECON HPS slabs constructed in November 2016 at the Elliott Aviation hangar on the north side of the Des Moines International Airport (DSM) were used as a baseline for estimating construction costs. Note that ECON HPS construction cost was adjusted costs from 2016 they were built to 2017 using time adjustment factor from RSMeans data base (Reininger 2018). Moreover, the different locations require adjustments to the construction costs based on location factors from RSMeans data on Building Construction Costs (Reininger 2018).

In addition, based on information obtained from DSM airport managers, cost of maintaining large-scale heated pavement system can be assumed to be 1% of its construction cost. Due to the unavailability of historical records regarding costs associated with maintenance of ECON HPS, subject matter experts' opinions (i.e. DSM maintenance managers) used to quantify maintenance cost of ECON HPS. "*Expert Judgement techniques are useful for quantifying models in situations in which, because of either cost, technical difficulties, or the uniqueness of the situation, it has been impossible to make enough observations to quantify the model with real data*" (Bedford et al. 2016).

Flight delay data was collected from the Bureau of Transportation Statistics (BTS) and the Research and Innovative Technology Administration (RITA) (BTS 2017) following BTS' definition: "*A flight is considered delayed if it arrives 15 or more minutes later than its scheduled time*". While there can be many causes of scheduled air-service delays, on average the fraction of weather-related delays occurring at the point of departure, is approximately 5% of all delays for all airports. While such delays are usually caused by extreme weather such as tornadoes, blizzards, or hurricanes (Bureau of Transportation Statistics 2017), most weather-related flight delays during winter are due to snowfall (WeatherBill 2017). For the purpose of this study, delays due to snow and ice removal were assumed to be approximately 3% of total operations. The percentage of weather-related delays was also included as one of the input variables in the stochastic cost model and the sensitivity analysis. After discussions with DSM airport managers, costs and benefits were also assumed to vary as a function of the airport area. Also, due to the existent sequence of flights on the air transport network, if a delay is avoided due to the material used, the airline may not face other flight delays or possible flight cancelations on the same network, meaning that other airports will also be impacted. The number of snow events for each studied location were collected from Automated Surface Observing Systems (ASOS) data (ASOS 2018) located at each airport.

The performance of ECON HPS at different locations is assumed to be similar to the ECON HPS slabs constructed at DSM. The annual average price of commercial electricity for last ten years (2007-2017) each studied location was obtained from the US Energy Information Administration (24) and used to estimate operational costs of ECON HPS for the new airports.

Stochastic Benefit Cost Analysis

When model outcomes are associated with significant uncertainties, Monte Carlo simulation (MCS) can be used to model the impact of interventions of input variables on the output (Gransberg and Diekmann 2004). In order to conduct the risk analysis using MCS, choosing appropriate distributions for the inputs variables is necessary. To capture the impact of those variables with high potential of uncertainty on the BCR, the following input variables were used in running MCS:

- Construction costs (USD/m^2)
- Duration of each delay (hours)
- Number of operations in one day
- Number of snow events at each year
- Percentage of weather related delays
- Trip purpose, ECON HPS electricity use
- Commercial price of electricity (USD/kWh)

The maximum likelihood method was used to fit the variables to a distribution and the best fit distribution was chosen based on the chi-squared goodness-of-fit test (Pearson 1992). FAA benefit-cost analysis guidance (FAA 1999) for major airport infrastructure projects suggests the adaption of a twenty-years economic life span beyond the completion of construction. In addition, for capturing discount rate fluctuations in the economic analysis and evaluating discount-rate sensitivity with respect to the Benefit Cost Ratio (BCR), the previous twenty-years (1997 to 2017) discount rate data from the Federal Reserve (Federal Rserve 2018) was obtained, fitted to the appropriate probability distribution, and added to the model. For the variables associated with limited sample data (i.e. construction cost and percentage of weather related delays), data was obtained from the DSM installation and a triangular distribution, which is an appropriate distribution for variables with limited data (Gransberg and Kelly 2008), was used. For the variables obtained using historical records and reflecting the best fitted distributions are shown in Table 1 and Figure 4-3.

Table 4-1 Distribution used for common variables among case studies

Input Variable	**Distribution**	**Standard Deviation**	**Description**
Construction cost (USD/m^2)*	Triangular	N/A	{ 225, 450, 675}
$\boldsymbol{E_c}$ **- Electricity use (Wh/m^2)***	Lognormal	25	μ=401
Tp - Trip purpose (-)	Discrete	N/A	59.6% personal 40.4% business
Discount rate (%)	Pareto	1.1	α=3.10

In addition to the common variables among all the airports, inputs such as: number of operation, snow events, duration of aircraft delays, and commercial electricity price would vary from one airport to another. All these aforementioned variables obtained from historical records and range and distribution associated with each inputs are exhibited in a log scale system (Figure 4-6).

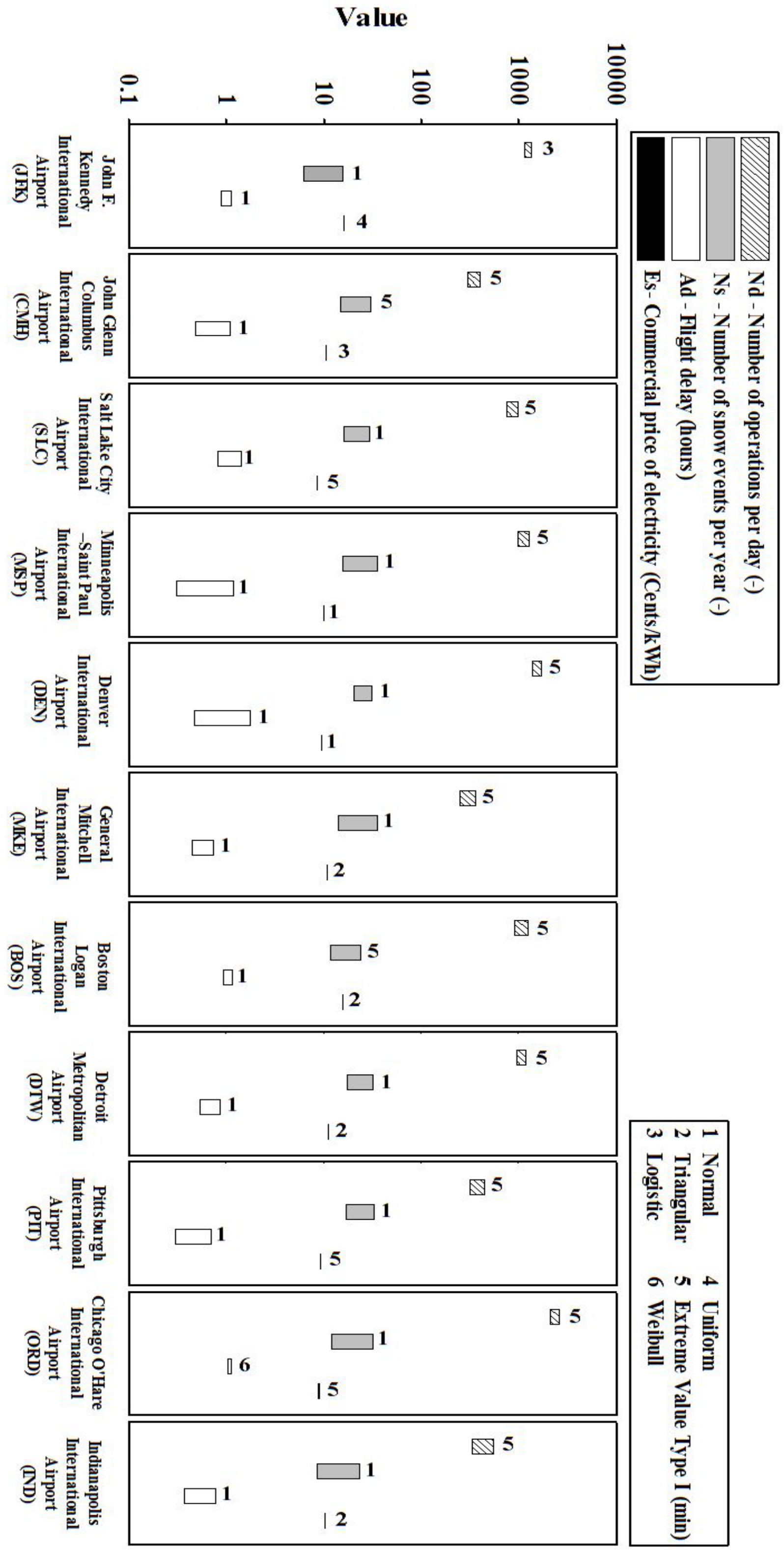
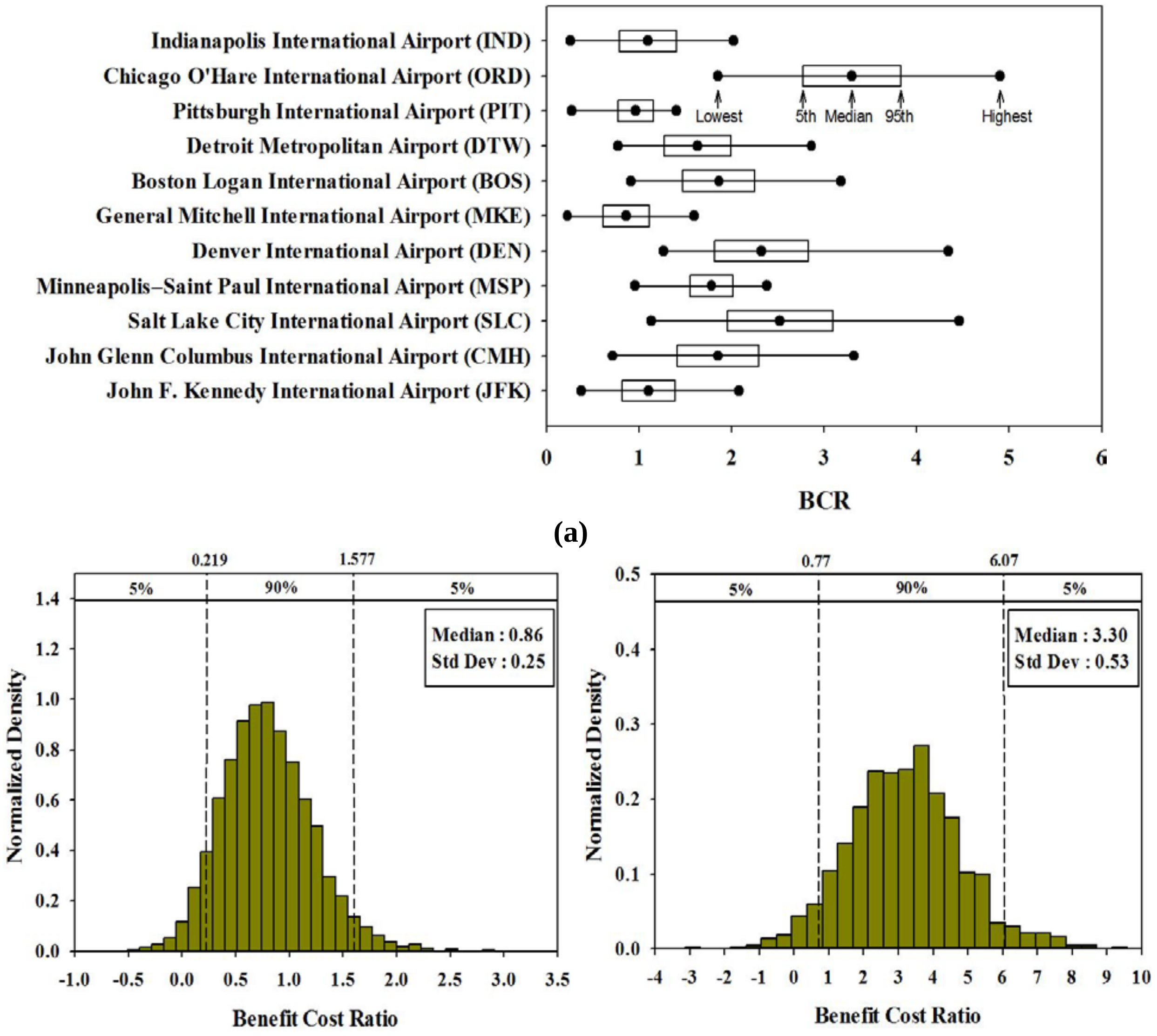


Figure 4-6 Individual input variables associated with each airport used analysis

Using the information presented in Table 4-1 and Figure 4-6, simulations were conducted to determine the probabilistic Benefit Cost Ratio (BCR). To conduct the stochastic LCBCA, the model was developed in Matlab, with each simulation iterated one million times, each lasting from 20 s to 55 s. The results from running MCS are probability density function (PDF) that provides a relative likelihood of BCR. The simulation results are summarized in Figure 4-7a. Standard deviations, estimated ranges with a two-tailed 90% confidence interval, and median values were presented for all the airports. Figure 4-7a Indicates that the median values for BCR are bigger than one in most of studied airports. In addition, for those case studies which had biggest (Chicago O'Hare International Airport) and smallest median values (General Mitchel International Airport) the probability density functions are shown in Figure 4-7b and Figure 4-7c respectively. After Chicago O'Hare International Airport (ORD), Salt Lake City International Airport (SLC), and Denver International Airport (DEN) have the highest BCR among other case studies respectively (Figure 4-7a). Note that, “*the median is a good measure because, regardless of distribution shape, half the values are above the median and half are below the median*” (Boddy and Smith 2009).



(a)

(b) **(b)**

Figure 4-7 BCR results; (a) summary of simulations, (b) PDF for ORD, PDF for MKE.

Another important outcome of running MCS is a relative likelihood that, when implementing ECON, benefits would outweigh costs in in all possible scenarios. The reliabilities that benefits to the costs of a potential ECON HPS projects are greater than one was mapped in Figure 4-8. This implies a general economic argument supporting action to make the investment.

Figure 4-8 shows that there are only two states (Wisconsin and Pennsylvania) which had BCR median values less than one, and other states investigated in this study showed higher values of BCR than one. Six different categories between 50% to 100% probability of benefiting from the

ECON HPS projects were considered in order to compare the states. Among the states with higher BCR median than 1, Utah, Colorado, and Illinois had 100%; Minnesota and Massachusetts had 90 to 99%; Michigan and Ohio had 80 to 89%; Indiana and New York had 70 to 79% probability of benefiting from the action. On the other hand, Pennsylvania and Wisconsin, which had lower BCR median than 1, had 60 to 69% and 50 to 59% probability of benefiting from the ECON HPS project, respectively.

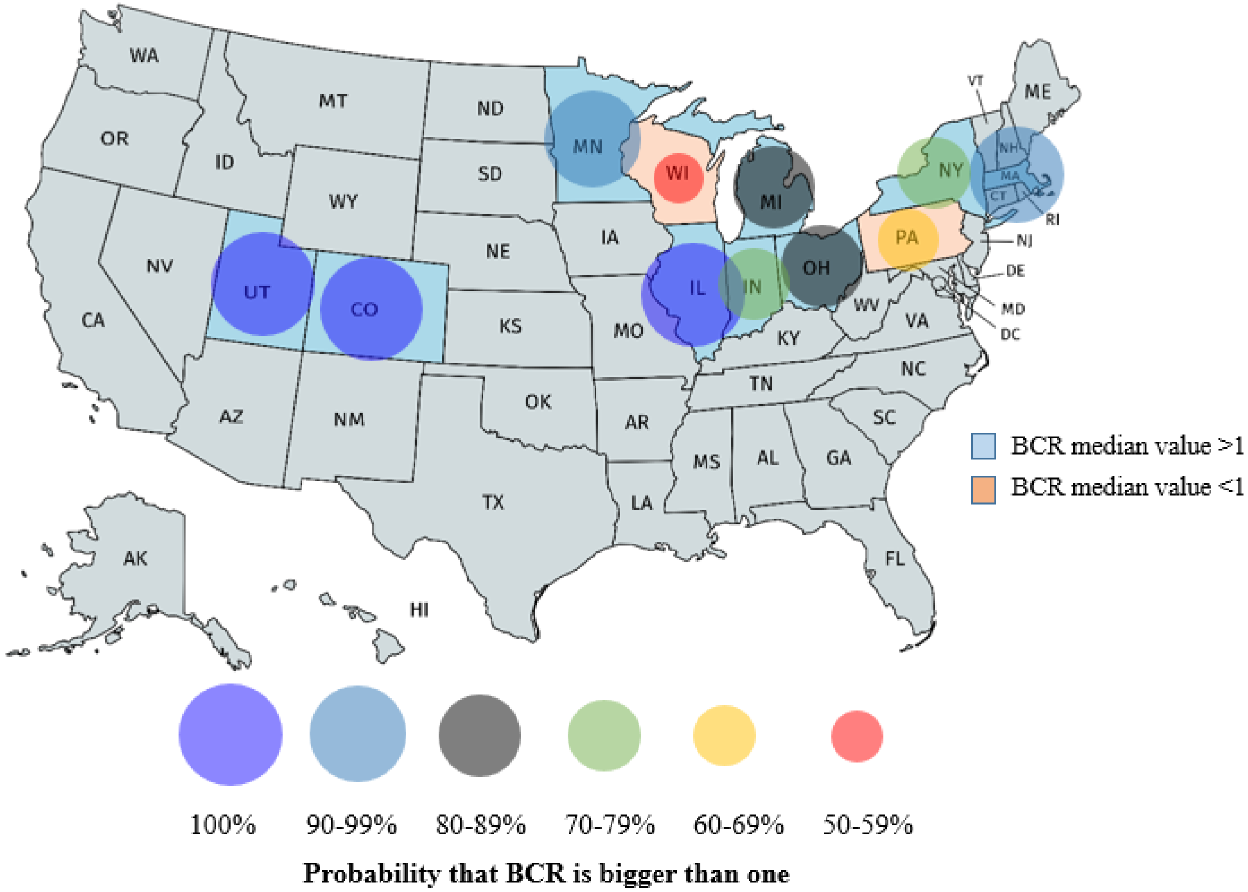
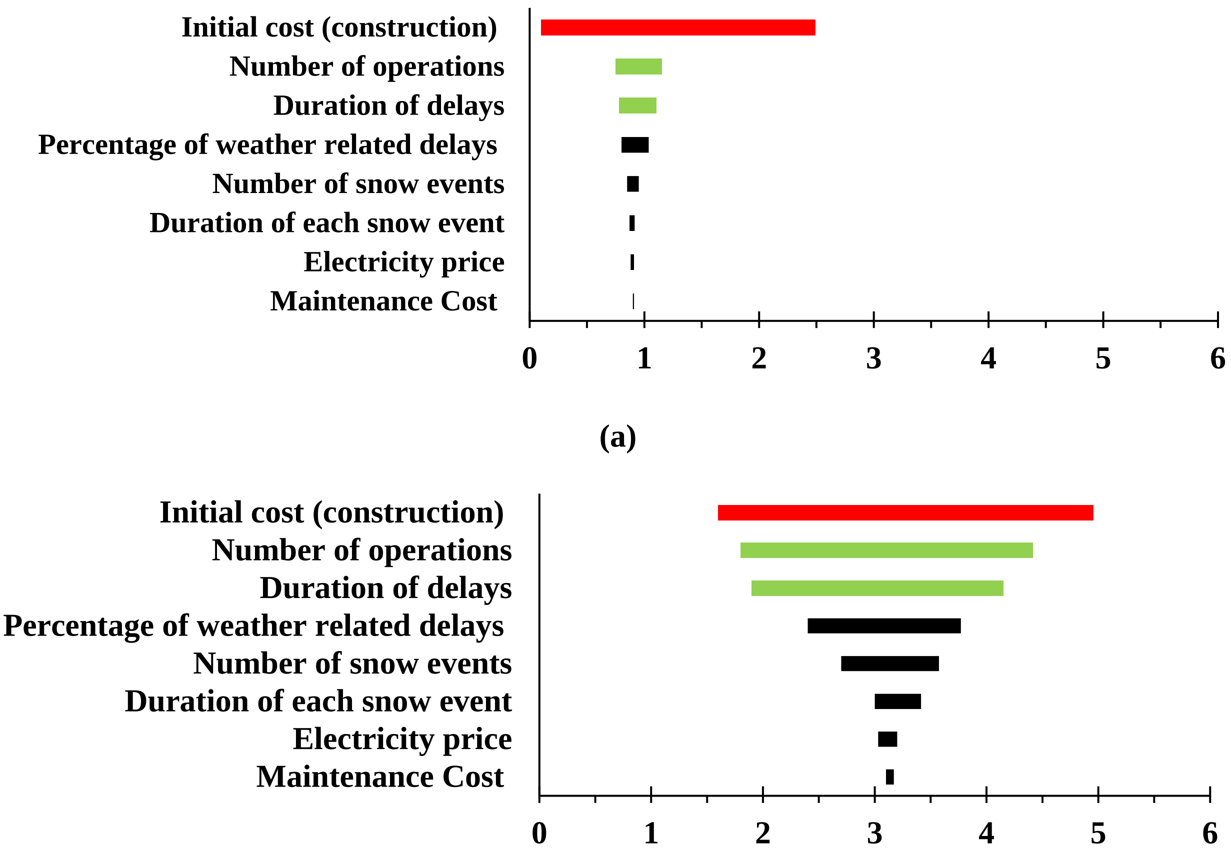


Figure 4-8 BCR likelihood of occurrence

As it is shown in Figure 4-8 the ECON HPS installation in ORD, SLC, and DEN would be the economic investment in all of the possible scenarios under the set of assumptions disused in this study. To determine which variable has the greatest impact on the BCR sensitivity analysis, using a one-at-a-time (OAT) method, was conducted for the case with highest and lowest BCR median values, which are ORD and MKE respectively. Figure 4-9 shows the sensitivity analysis results which present two tornado graphs.



(b)

Figure 4-9 Tornado graph of Monte Carlo simulation (MCS) based sensitivity analysis results; (a) MKE, (b) ORD airports

Figure 4-9 shows that the initial construction costs, which is highlighted with red, is the most influential factor in both, and it is expected that as the construction cost decreases the BCR value would increase. In fact, the ECON HPS construction cost is the major factor that drives the BCR below one for the MKE case. Findings of the sensitivity analysis in both cases suggest that along with construction cost, other important factors influencing BCR are number of operations and duration of delays (which are highlighted with green). However, for larger airports such as ORD, number of operations and duration of delays had a huge influence on BCR. The result of analysis shows that how size of the airports (in terms of number of operations) would influence the BCR of implementing ECON HPS.

It was also anticipated that the use of ECON HPS at airports that experience harsh winter events with frequent snowfalls would benefit the most. However, result of sensitivity analysis showed that number of snow events is the fifth factor among total eight factors evaluated in this study that affects BCR. As mentioned in this section, size of the airports in terms of number of operation is the main factor which can drives BCR above one. Therefore, it is logical to expect that airports with large number of operations that experience winters with low snowfalls frequency might benefit from ECON HPS placement.

Apart from the direct increase in benefits expected to result from an increase in number of operations, it is also possible that economies of scale, cost per unit of output decreasing with increasing scale, could affect the economic analysis results, although this factor was not directly assessed in this analysis. Moreover, this analysis does not consider the network benefits, because for example, a flight in Florida might delay because the previous flight was departing from Minnesota; by avoiding the Minnesota delay, it is possible to also avoid the passenger, airport, and airline costs in the following Florida flight.

Financing

Use of heated pavement systems at airports requires a significant amount of investments. Therefore authorities (e.g. airports or airlines) may need to finance heated pavement projects. “*Project finance is the financing of long-term infrastructure, industrial projects and public services using a non-recourse or limited recourse financial structure*” (Grimsey and Lewis 2002). The incomes made by project would be used pay back the resources and expenditures utilized for financing. Based on the project, different financing options might be available (e.g. private financing, public source, federal programs and etc.). Bank loans are one of the most popular source for construction financing (Qian and Yeung 2015). There is a range of the options for getting loans from banks that would vary depending on ownership, financing, risk allocation and duration of the project (Chege 2001). This paper does not aim to go into details about the different financing options available for financing a construction project but rather it aims at providing some insights about participation of financial institutions in implementing ECON HPS for apron areas.

At this end, ORD, where the benefit cost ratio of ECON HPS installation has the highest and lowest median values, was considered to evaluate financial feasibility of implementing such technologies in airports. Also it was assumed that a constant rise in price of each ticket would compensate the loan periodic payments. This ticket price increase is due to increase in snow removal technology and operation (use of heated pavement systems). Once considering the costs increase there are four options (i) airport is financing the construction and increases the passenger fee which is charged along with the ticket, meaning that the passenger will be paying for the construction; (ii) airline is financing the construction and they are passing the costs increase to the passenger; (iii) airport is financing the construction and they assume the cost increase; and (iv) airline is financing the construction and they assume the cost increase. This study considered option (ii). However, the difference between those four options were not considered in this study. Also, for options (i) and (ii) the cost increase leads to an increase on ticket price, which might cause a decrease on air transport demand.

In order to conduct financial analysis following assumptions have been made:

- Loan was considered as series of future annual payments.
- The total number of seats in a mid-sized aircraft is about 150. The average overall load factor for U.S. domestic flights in 2017 was 84.5%. This translates to 84.5% of 150 seats being occupied, which gives a value of 125 seats (tickets).
- Construction loan interest rates vary along with market interest rates, different interest rate evaluated (from four to ten percent).
- Similarly, to understand the impact of different loan periods on future periodic payments, different loan durations were used (i.e. ten years to twenty years).

The loan payment formula, which is the same formula as the one for payments calculations on an ordinary annuity (Park 2007), was utilized to determine the payments on a loan (Equation 1)

$$P = \frac{r \times (PV)}{1 - (1 + r)^{-n}} \qquad (1)$$

Where P is future periodic payments, PV is present value of investments, r is rate per period (annually in this paper), and n is number of periods. Figure 4-10 shows rise in price of each ticket based on different interest rate and loan period scenarios.

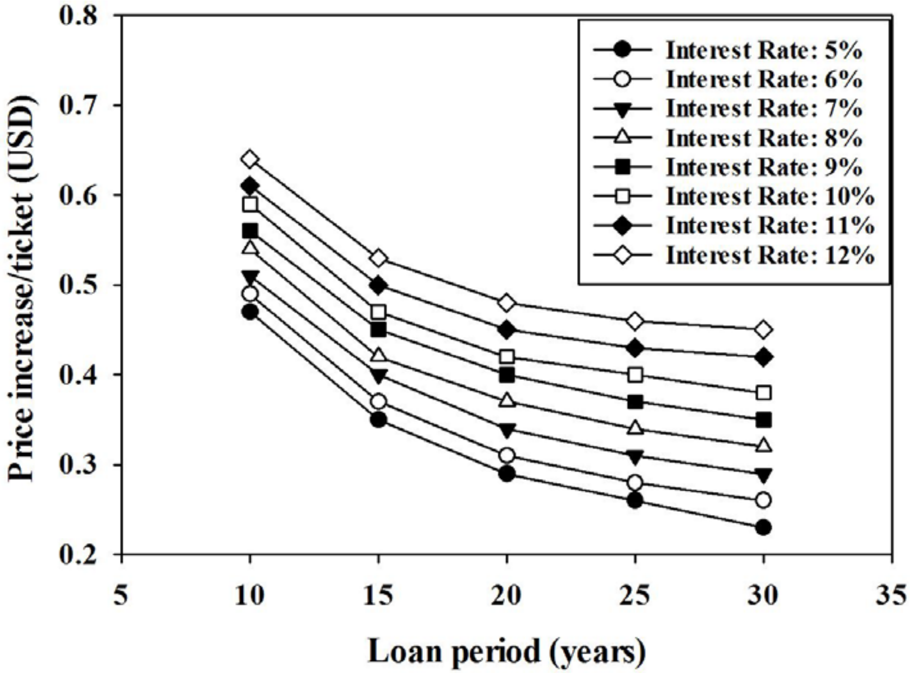


Figure 4-10 Rise in price of each ticket based on different interest rate and loan period

As it is shown in Figure 4-10 under different circumstances rise in price of each ticket would vary from 25 cents to 65 cents. As mentioned before, the increase in the thicket price is result of increase in the airport snow removal operation cost. Note that the change in demand due to ticket price increase was not calculated for this study. Those differences and demand impact might be considered in future studies.

Discussion

The potential benefits of ECON HPS are numerous. The installation of such systems can potentially reduce the dependency on SRE and deicing chemicals. In addition, HPS have the capability to provide enhanced safety for ground staff and vehicles, reduce the labor of snow and slush removal, and create better working conditions at the airport. These workers are employed either by the airport or the airlines depending on airports or airlines policies. Potential accidents can cause additional monetary burdens to the airports or airlines. However, a major challenge in estimating benefits associated with safety enhancement is number and injury severity levels associated with each incident, which airports and airlines usually do not publish such information. Along the same line, this study only estimated the economic impact of installing ECON HPS for domestic flights, as certain airports in the study do not cater to international flights. International delays are complicated to estimate due to their routing and knowledge of the delay. Such delays may be considered in future studies.

Conclusion

The main objective of this study was to conduct a stochastic economic analysis to evaluate the economic performance of electrically conductive concrete heated pavement systems (ECON HPS). This study estimates the costs and monetize the benefits associated with ECON HPS and provide enhanced information for decision maker such as airport mangers, developers, airlines, and investors with information. In addition, feasibility of financing option (loan) was explored for different interest rates and loan periods. The key findings and recommendations based on results of this study were summarized below:

- Results of running Monte Carlo simulation (MCS) indicates that benefit cost ratio of ECON HPS installation has the highest and lowest median values in the ORD and MKE respectively.
- The benefits of ECON HPS placement, including reduction in passenger delay time and air fuel consumption, outweigh the construction and system operational costs in the DEN, ORD, and SLC.
- Benefits of installing ECON HPS at the MSP and BOS exceeds the costs with more than 90% reliability.

- Construction cost was the most significant factor affecting benefit cost ratio (BCR). By improvements in ECON materials technology (e.g., improving the conductivity of the system) and advancements in construction practices (e.g., increasing contractor knowledge and experience) initial construction cost of ECON HPS may decrease, which has a huge impact on BCR.
- Some airports may only benefit from use of ECON HPS in portions of the apron area, so it is crucial to investigate strategic installation of ECON HPS.
- Result of sensitive analysis showed that BCR along with construction cost largely depends on and size of the airports, in terms of aircraft operations. For example, in the ORD case, duration of delays and number of operations had significant influence on BCR. However, the impact of number of operations in the case of MKE was much lower than construction cost. This difference mainly depends on larger number of aircraft operations at ORD.
- Result of sensitivity analysis also showed that snow events quantity is the fifth factor among total eight items evaluated in this study that affects BCR.
- Under different financing circumstances (e.g. loan periods and interest rate) rise in price of each ticket would vary from 25 cents to 65 cents.

The methodology followed in this paper could be extended to study the economic viability of other similar technologies, such as geothermal heated pavement systems (Wang et al. 2008) in blend with superhydrophobic materials (Arabzadeh et al. 2017; Nahvi et al. 2017).

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CHAPTER 5. DETERMINISTIC AND STOCHASTIC LIFE-CYCLE COST ANALYSIS FOR OTTA SEAL SURFACE TREATMENT

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Abstract

The U.S. has approximately 1,417,000 miles of unpaved secondary roads that experience relatively low daily traffic volume. To maintain such roads, U.S. county secondary road departments spend millions of dollars annually for aggregate replacement alone. Meanwhile Otta seal has been reported as a low-cost bituminous surface treatment (BST) and dust mitigation technique by many international studies. However, only two U.S. states - Minnesota and South Dakota – have reported on its construction and performance. In consideration of its limited use in the US, Otta seal could be compared with chip seal - a commonly used BST in the U.S - from a economic viability perspective. Using Minnesota as a case study location for life-cycle cost analysis, an analysis was conducted at two levels: (I) deterministic life-cycle cost analysis, and (II) stochastic life-cycle cost analysis. Based on results of these analyses, it was concluded that the Otta seal could potentially be a economic viable BST, and public agencies could use it to reduce maintenance cost of low-volume roads, especially when gaining access to uniformly graded aggregate which is commonly used for chip seals is not viable.

Key words: Otta seal, Life-Cycle Cost Analysis, Minnesota, Chip seal, Monte Carlo simulation

Introduction

Maintenance is vital to the sustainability and serviceability of low-volume roads. Many such roads are surfaced every year in the U.S. with chip seal, a treatment that requires good-quality aggregate can be associated with a high cost of hauling. Budget decreases combined with increases in infrastructure demands are expected in the next ten years (Newman and Casey, 2008), providing reasonable motives that could drive public agencies to find less expensive and more effective approaches to meet the expected growth in demands on infrastructure (Lee et al., 2016).

Otta seal technology, originally developed in the 1960s, has been widely in Northern Europe and Africa, as an economic and practical alternative to conventional bituminous surface treatments (BST) (Overby 1999). Compared to other BST methods traditionally used in the U.S that require high-quality materials and specialized expertise, Otta seal can more often use local aggregates for surface treatment, substantially reducing construction-related costs (Overby and Pinard, 2012). Otta seal can be laid down in either one or two layers depending on traffic volume, construction cost, and required service life (Johnson, 2011, 2003; Skorseth, 2013).

Similarly to other BST methods, Otta seal adds no structural capacity to a roadway (f 1999; Overby and Pinard 2013, 2012), so adequate substructure support is required to accommodate anticipated traffic-related loads. However, there are several advantages frequently associated with Otta seal: (I) it more often allows the use of local aggregate to reduce the cost of aggregate production and transportation; (II) it does not require the use of a prime coat (a thin film of liquid asphalt emulsion or cutback which soaks into the base binds subsequent treatment layers to the base; (III) it can be opened to traffic immediately after construction; (IV) it requires fewer periodic maintenance activities between reseals; and (V) it helps to lower fugitive dust emissions (Johnson, 2011; Overby and Pinard, 2007; Pinard, 2013; Skorsetch et al., 2015). Various agencies (city and county, as well as DOT) in Minnesota have since early 2000 used Otta seal for a range of traffic volumes ranging from very low up to 2,000-vehicle average annual daily traffic (AADT) (Johnson, 2011, 2003). Most Otta seal surfaced road sections constructed in Minnesota have performed well with few cracks visible on the surface except when unexpected circumstances such as unanticipated high traffic volumes or flood damage arose (Johnson, 2011).

Existing studies (Overby and Pinard, 2013) have reported Otta seal's lower life-cycle costs compared to other BSTs, but the weakness of these studies lies in their assumptions. A deterministic analysis of life-cycle costs assumes a given cost for the materials used in the surface treatment. However, assuming that today's cost of liquid asphalt binder would be inflated at an annual rate of 3% to 5% over a period of a decade or more would be a fundamental mistake. The price of diesel fuel has nearly tripled over the past decade, as have the prices of bituminous products. Such instability means that deterministic economic analysis cannot be performed with any degree of confidence when applied to highly-volatile construction materials (Gransberg and Diekmann, 2004; Gransberg and Kelly, 2008; Gransberg and Scheepbouwer, 2010). In addition, impact of different input variables (e.g. cost of binder, transportation cost, discount rate and so on) on annual maintenance of Otta seal was not reported previously.

The objective of this study was to evaluate the economic viability of Otta seal through a stochastic life-cycle cost analysis (LCCA) conducted specifically for the state of Minnesota. This study sought to explore the cost-effectiveness of Otta seal as an alternative surface treatment to chip seal. Moreover, using stochastic sensitivity analysis, this research determines which among all the input variables has the greatest potential impact on the overall EUAC. Various road and highway agencies in Minnesota has implemented Otta seal and have provided access to the historical cost records needed to complete this study. Therefore, this paper examines the implementation of Otta seal in the state of Minnesota.

Methodology

Stochastic and deterministic Life-Cycle Cost Analysis (LCCA) approaches were employed to compare competing design alternatives. The specific approach for this study utilizes equivalent uniform annual cost (EUAC) analysis, permitting elimination of many assumptions required when using the more common, and more problematic, net present worth LCCA (Walls and Smith 1998). Deterministic EUAC, the traditional method used for decision-making in pavement management, involves using point estimates that result in a single output value (Babashamsi et al., 2016; Salem et al., 2003).

The outcome of a deterministic LCCA depends on numerous estimates, forecasts, assumptions, and approximations, with each factor having some potential to introduce error into the results. The role of each such error in affecting the outcome of the EUAC must be known to a decision maker if informed decisions are to be made with confidence. Moreover, the degree of uncertainty associated with each alternative is itself a factor to be considered when selecting among competing alternatives (Amini et al., 2012; Ferreira and Santos, 2013; Gransberg and Scheepbouwer, 2010; Salem et al., 2003; Walls III and Smith. R, 1998).

Stochastic LCCA

Along with deterministic LCCA, this study included the use of stochastic LCCA methodology (Pittenger et al., 2012) like that previously used in studies related to pavement management (Abdelaty et al., 2016; Anand et al., 2017; Gransberg and Diekmann, 2004; Nahvi et al., 2018; Sri, 2017; Tighe, 2001). This methodology was specifically developed to accommodate the wide range of surface treatment alternatives found in pavement preservation and maintenance approaches (Tighe, 2001). The issues associated with a deterministic EUAC model, like sensitivity to discount rate or volatility of underlying commodity prices, could be addressed by developing a stochastic life-cycle cost model. A stochastic LCCA approach allows input variables to range across their more recent historic variations utilizing a Monte Carlo Simulation (MCS) (Reigle and Zaniewski, 2002). MCS also supports quantification of the range of possible EUAC values by performing sensitivity analysis to identify how each particular input variable affects the overall EUAC model (Flanagan et al., 1987; Reigle and Zaniewski, 2002).

Input values determination

The first step in a stochastic approach is to determine which input values have associated uncertainty that will have significant impact on the results (Peshkin, D. et al., 2004; Pittenger et al., 2012) (Peshkin, D., et al., 2004; Pittenger, et al., 2012). Such values should be treated probabilistically while others are treated deterministically to simplify the analysis (Pittenger et al., 2012). Initial construction costs, discount rates, and service life of pavement treatment methods were treated probabilistically in the stochastic LCCA study.

Service life and discount rate

“Service life is considered the most superior performance measure because all other long-term effectiveness measures are computed on the basis of service life”(FHWA, 2007). Service life uncertainty creates sensitivity in LCCA results (Gransberg and Kelly, 2008), making it a good candidate for stochastic treatment and deterministic sensitivity analysis.

Figure 5-1 summarizes service lives of single chip seal, double chip seal and double Otta seal for LCCA calculations, as supported in the literature (Ceylan et al., 2018; Gransberg, 2008, 2007; Gransberg and James, 2005; Overbay, 1999; Overby and Pinard, 2013, 2012). In addition to the literature review many site visits were conducted by research team to explore the longevity of Otta seal and chip seal roads. The results of site visits show that Otta seal and chip seal service life was within a range that mentioned in the literature.

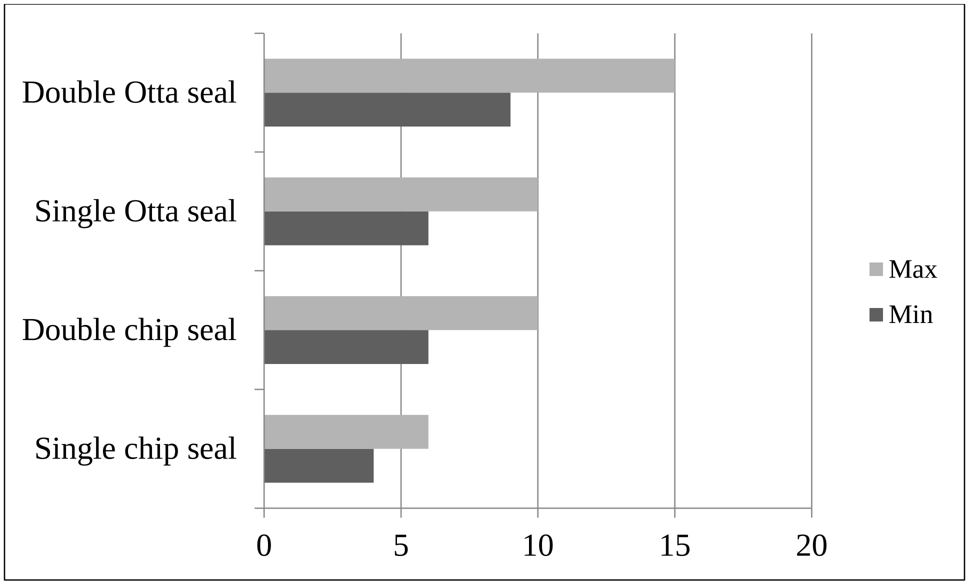


Figure 5-1 Typical service life ranges for bituminous surface treatments

FHWA suggests that a discount rate of 3% to 5% be used in determination of LCCA (FHWA Pavement Division, 1998). In addition, for stochastic LCCA approach previous twenty-year discount rate data from the Federal Reserve (Federal Rserve, 2018) was obtained.

Initial cost

Initial construction cost is one of the main components of LCCA (FHWA Pavement Division, 1998). One cost estimation approach would be to use bid tabs to create unit cost estimates. Another approach that was attractive due to limited availability of Otta seal bid data was to break down the initial cost into specific items, such as aggregate or transportation. Each item's quantity and cost were estimated for use in deterministic and stochastic LCCA models.

Initial cost estimation using bid data

The initial construction cost of BST was obtained from Minnesota bid tabs that are publicly available (Bid Express, 2018). Bid data provide a simple, reliable, and quick method for estimating unit costs (Tehrani, 2016). The data set used in this analysis contained bid records obtained over the previous three-year period (June 2015 to June 2018). In total seven bid records for double Otta seal, eleven for double chip seal, and six for single chip seal were found. Figure 5-2 shows how unit costs of various Minnesota surface treatment options were distributed from September 2015 to August 2017.

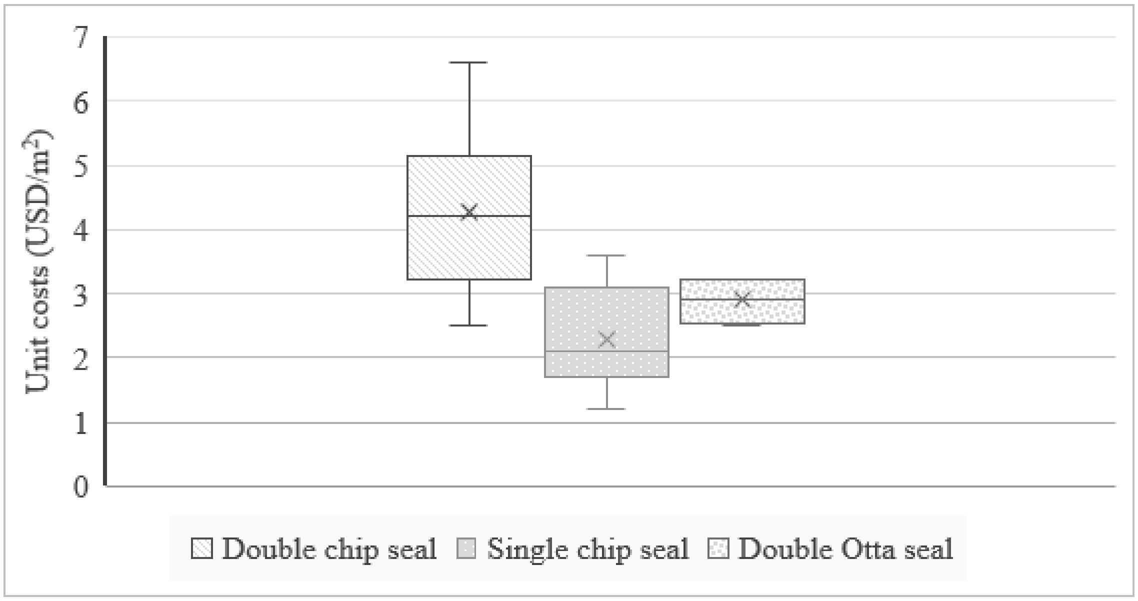


Figure 5-2 Unit cost of surface treatment options

According to design guidelines, the volume of binder in double Otta seal is usually close to 2.25l/m^2 (0.50gal/yd^2). This would be virtually 50 percent more than that of double chip seal (Gransberg, 2007; Gransberg and James, 2005; Overby and Pinard, 2013, 2007). However, as shown in Figure 5-2, the mean values of unit costs for double Otta seal projects is much less than that for double chip seal.

According to discussions with contractors and Minnesota county engineers, the main reason for this difference between unit prices of chip seal and Otta seal lies in the cost of hauling aggregate from aggregate producers’ storage areas to job sites; in some chip seal cases the hauling distance would be more than 300 km.

Also, since Otta seal has a less restricted requirement for aggregate gradation (unlike chip seal that requires using a uniformly graded aggregate, as shown in Figure 5-3), using local aggregate for Otta seal surfacing is more often a viable option that could result in aggregate production and haulage cost reduction (for locations not close to a good source of chip seal aggregate), reducing construction unit cost accordingly.

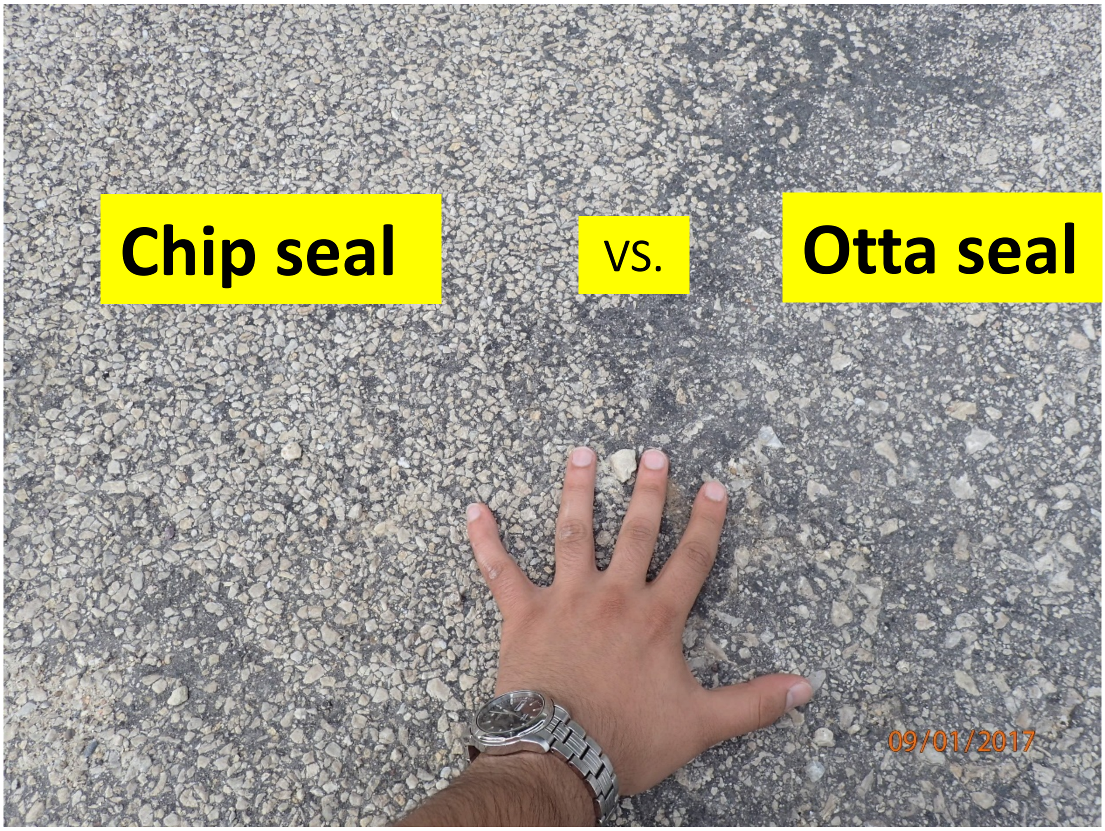
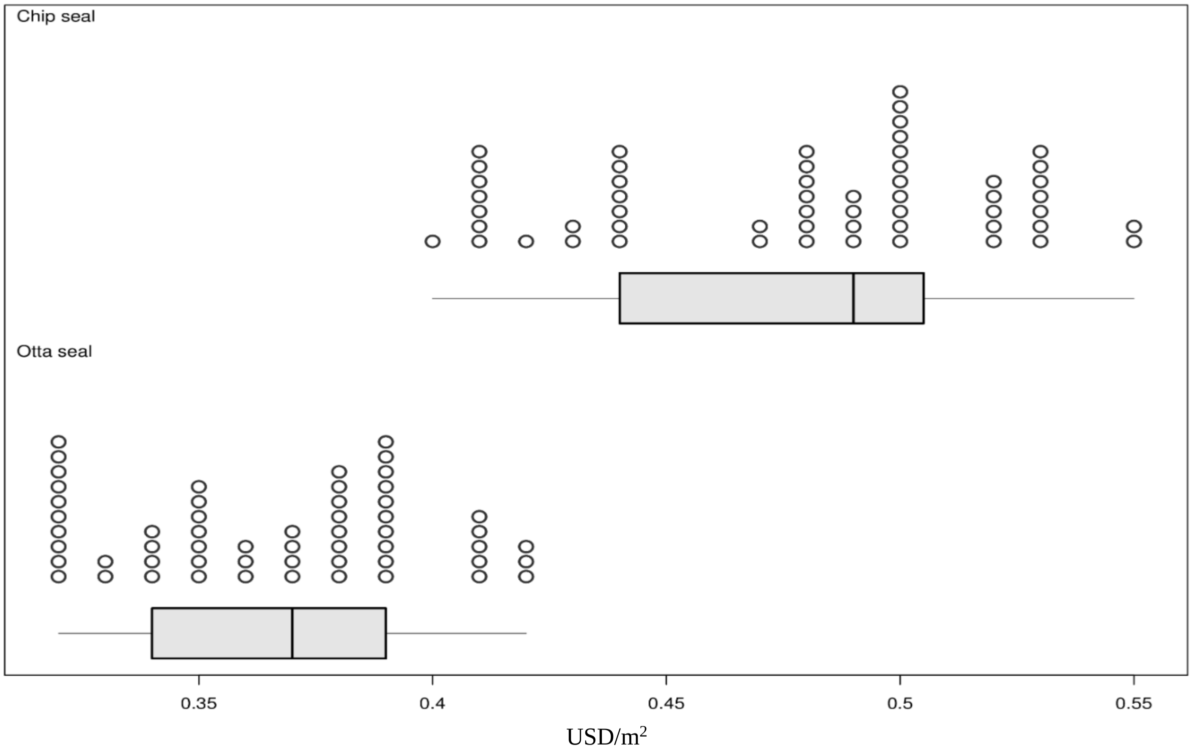


Figure 5-3 Uniform and non-uniform gradation of Chip seal and Otta seal (MN74, Winona County, MN)

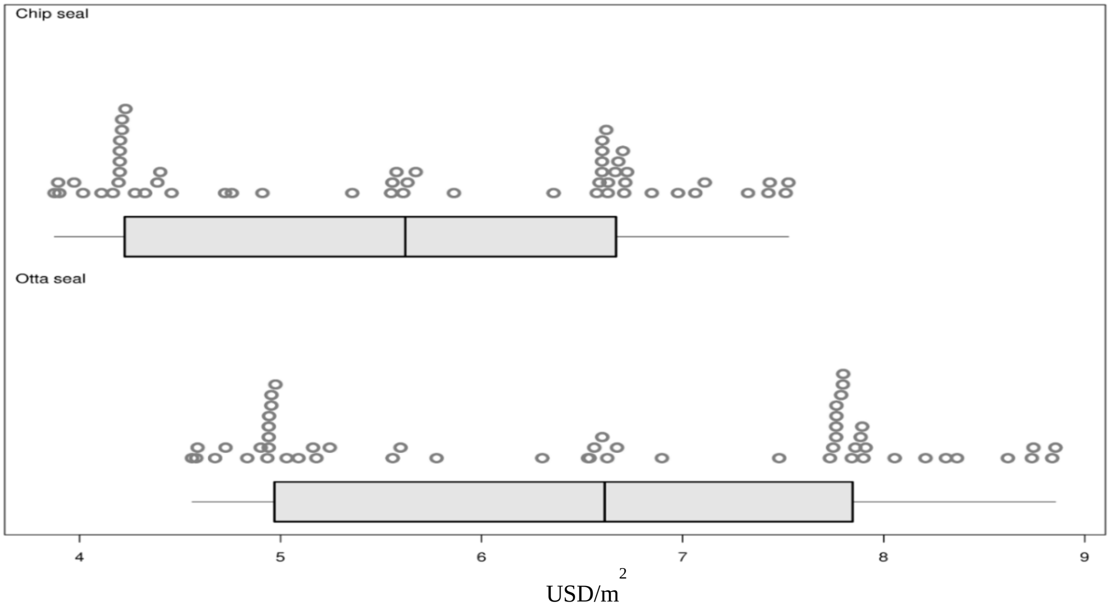
Initial cost estimation using cost breakdown approach

Due to the limited number of recent Otta seal projects in, there is only a limited available bid data available; in particular, there have been no single-layer Otta seal project in the State of Minnesota during the past four years. Therefore, initial installation costs of surface treatment methods were broken down into specific commodities such as aggregate, transportation, and binder. Both Otta seal and chip seal use aggregate that is spread on top of a bituminous binding agent after which the surface is rolled with a pneumatic-tired roller, so the construction sequence and equipment required for Otta seal and chip seal construction are quite similar. Furthermore, the same equipment (asphalt distributor, chip spreader, pneumatic roller, and mechanical broom) can be used in either case, thus equipment cost are likely to be similar for both methods. Otta seal production rate is a bit lower, because it requires more material. Every time the distributor runs out of binder there is a delay while it is refilled. If more aggregate spreading is needed, then more trucks are required, and more truck changes slows construction down. Despite these differences, they may not have too big of an impact on cost. Therefore, equipment and labor cost for both sealing methods would be close to each other and will not have a material effect on the comparison.

The main sources of initial cost difference between the methods are quantity of binder, aggregate haulage, and type and quantity aggregate used. In this study these costs were determined from the U.S. Bureau of Labor Statistics (BLS) data (“Commodity Data Database, Producer Price Index. U.S.,” n.d.) and quarterly cost reports presented in the Engineering News Record (Engineering News Record, 2018) (Figure 5-4).



(a)



(b)

Figure 5-4 Historical cost of required materials for sealing one square meter surface during last five years; a) Aggregate: MN class 5 for Otta seal and graded aggregate for chip seal b) Cost of binder for chip seal and Otta seal

Figure 5-4a shows the historical cost of required aggregate per one square meter of both Otta seal and chip seal. The aggregate spreading rate for Otta seal is approximately 27kg/m^2 (50lb /yd^2) (Johnson 2011; Overby 1999; Overby and Pinard 2013) and for chip seal approximately 16kg/m^2 (50lb /yd^2) (Gransberg and James, 2005). As mentioned earlier, local aggregate materials are often used for Otta seal. In previous Minnesota Otta seal projects, MN Class 5 with a maximum aggregate size ranging from 1.25 to 2.5cm (0.50 to 1.00 inch) (Johnson, 2011) was used, while aggregates in chip seal construction ranged from 1cm (0.385 inches) up to 1.25cm (0.50 inches) (Ceylan et al., 2018; Overbay, 1999).

For a gravel road, the required amount of binder for Otta seal would be approximately 2.25l/m^2 (0.5gal/yd^2) (Johnson, 2011; Overby and Pinard, 2013) and for chip seal would be approximately 1.6 l/m^2 (0.35 gal/yd^2) (Gransberg and James, 2005). Figure 5-4b depicts the historical cost of required binder for one square meter of Otta seal and chip seal.

Another factor affecting initial cost is the cost of hauling aggregate from quarries to jobsites. The aggregate hauling rate per mile for the last five years in the state of Minnesota was obtained from the U.S. Bureau of Labor Statistics (BLS) data ("Commodity Data Database, Producer Price Index. U.S.," 2017). Figure 5-5 shows the cost per mile for hauling one truck load from an aggregate-producing location to a job site.

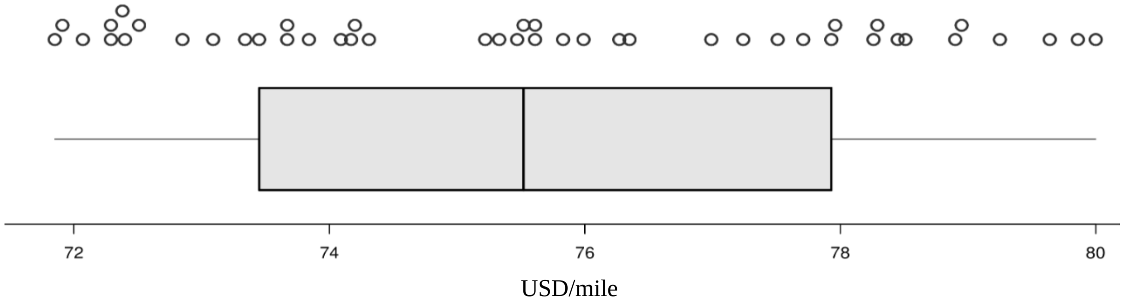
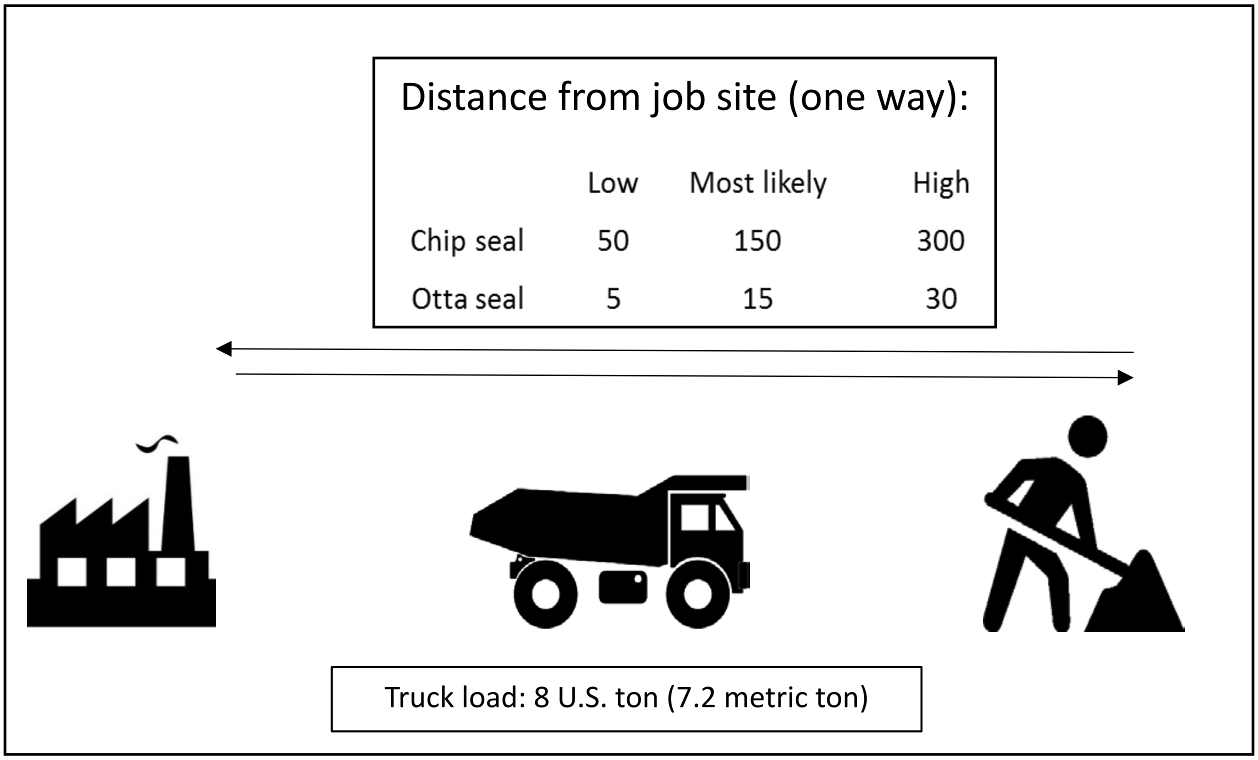


Figure 5-5 Hauling aggregate rate per mile for each truck load (7.2 metric ton)

Transportation cost is location-dependent and varies from one project to another. As shown in Figure 5-6 in the deterministic model three different scenarios for representing transportation cost were evaluated, while for the stochastic LCCA approach, transportation unit costs for all three possible scenarios were fitted to their best distributions and entered into the model.



Distance from job site (one way):

	Low	Most likely	High
Chip seal	50	150	300
Otta seal	5	15	30

Figure 5-6 Different scenarios for transportation cost

User and future costs

According to FHWA, “if a pavement treatment is expected to incur costs, such as maintenance, comparable to the costs of other alternatives and will not have a material effect on the output, they can be treated deterministically or ignored altogether”(Abdelaty et al., 2016; FHWA Pavement Division, 1998; Santos and Ferreira, 2013).

However, according to the literature and discussion with county engineers, the wheel path of a new reseal surface will usually flush before chip seal has reached its service life (Gransberg, 2008; Gransberg and James, 2005). This condition typically occurs roughly 2 to 3 years after construction (Gransberg, 2008). The cost of removing excess binder in cases in which the wheel paths flush was estimated using average bid prices for projects awarded in the state of Minnesota (“Bid Letting,” n.d.). The removal of excess binder also will typically add one more year to chip seal service life.

Based on discussion with Minnesota county engineers, all other maintenance costs associated with the road are assumed to be the same for both alternatives. In addition, since typical average daily traffic will be quite low, costs associated with traffic control during construction and maintenance was not considered in this study.

Selection of appropriate probability distributions

Choosing an appropriate probability distribution for each input variable is an important step in the stochastic LCCA approach, so input variables representing sufficient uncertainty and capability to significantly impact the BCR model were fit into proper distributions and entered into the model.

In this study, two methods, based on availability of data for different variables, were used to identify the appropriate probability distribution for each input variable. Variables with sufficient data availability were fit into their best fit distribution and entered into the model. The fitting process was enabled by goodness-of-fit tests based on statistical methods such as chi-square tests (Pearson, 1992). For other inputs (e.g. service life) triangular distributions, commonly used for variables based on limited sample data (Pittenger et al., 2012), was used.

Since Otta seal is a relatively new technology in the U.S., since there were only a few Otta seal projects implemented during last two years, a triangular distribution was used in the MCS model to represent initial cost of double Otta seal. The initial costs of single chip seal and double chip seal, obtained from the bid records, were fitted to the best theoretical distribution. Also, to make a same base comparison, chip seal alternatives were fitted triangularly and the results compared. In the stochastic LCCA approach based on cost breakdown, the historical unit cost of materials and transportation cost were replaced with their probability distributions, and the output was estimated in quantity variation format (as shown in Figure 5-7).

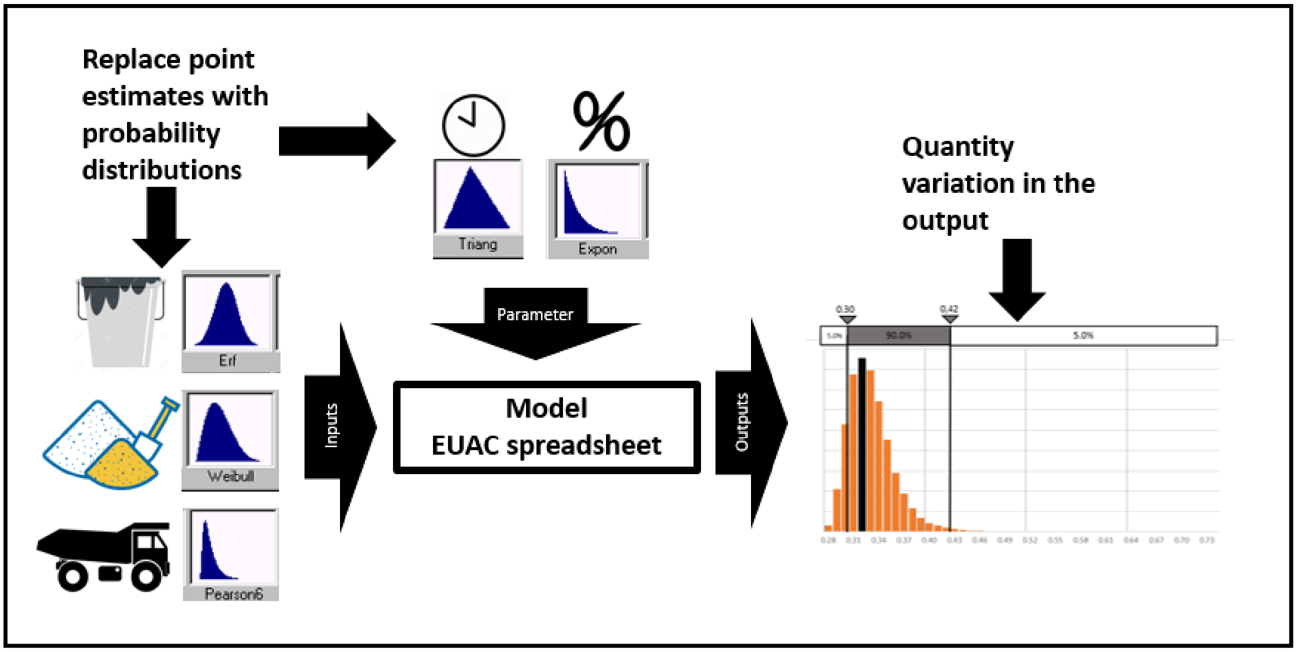


Figure 5-7 Stochastic cost model components

Result and discussion

The results of deterministic and stochastic LCCA are as follows:

Deterministic LCCA based on bid data

The mean value of bid data unit costs was used for initial costs. Table 1 shows the LCCA outputs in equivalent uniform annual cost format. The highest possible value of the double Otta seal option is lower than lowest possible value of chip seal options, as shown in Table 1. There is a theoretical possibility that a rapid change in material price of chip seal could put its EUAC at the high end of its range, so further analysis is required before it can be concluded that double Otta seal is the preferred alternative.

Table 5-1 Deterministic life cycle cost analysis (LCCA) based on bid data approach through the inclusion of a sensitivity analysis, equivalent uniform annual cost (EUAC) (USD/m2)

Treatment method	**Service life (years)**	**Discount rates**		
		3%	**4%**	**5%**
Double chip seal	Low (6)	0.70	0.72	0.76
	Most likely (8)	0.56	0.59	0.61
	High(10)	0.48	0.50	0.53
Double Otta seal	Low (9)	0.42	0.43	0.44
	Most likely (12)	0.34	0.35	0.36
	High(15)	0.28	0.29	0.31
Single chip seal	Low (4)	0.83	0.85	0.86
	Most likely (5)	0.67	0.68	0.70
	High (6)	0.56	0.58	0.59

Deterministic LCCA based on cost breakdown approach

To illustrate where the EUAC will fall, deterministic LCCA based on the FHWA model was performed using the lowest, the most likely, and the highest possible values for each input (Table 2). A discount rate of 3% was used in conformance with the FHWA technical report (FHWA Pavement Division, 1998). A 3% discount rate also reflects the highest cost value for agencies within FHWA guidelines-.

Table 5-2 Deterministic life cycle cost analysis (LCCA) based on cost breakdown approach through the inclusion of a sensitivity analysis, equivalent uniform annual cost (EUAC) (USD/m2)

Item		**low volume**	**most likely**	**high value**
Binder cost for chip seal (l/m^2)		3.89	5.60	7.50
Binder cost for Otta seal (l/m^2)		4.52	6.55	8.81
Aggregate cost for chip seal (kg/m^2)		0.81	0.99	1.13
Aggregate cost for Otta seal (kg/m^2)		0.63	0.72	0.86
Sealing types	**Service life (years)**	**EUAC (USD/m^2)**		
Double chip seal	High (6)	0.53	0.73	1.03
	Most likely (5)	0.43	0.59	0.84
	Low (4)	0.36	0.50	0.71
Double Otta seal	High (10)	0.20	0.28	0.35
	Most likely (8)	0.25	0.34	0.42
	Low (6)	0.32	0.44	0.54
Single chip seal	High (10)	0.40	0.58	0.84
	Most likely (8)	0.49	0.71	1.02
	Low (6)	0.64	0.91	1.32
Single Otta seal	High (15)	0.22	0.37	0.48
	Most likely (12)	0.24	0.44	0.58
	Low (9)	0.30	0.47	0.61

Similar to the deterministic analysis based on bid data, for most scenarios the cost of Otta seal implementation is relatively lower than that of chip seal. However, as mentioned in the Methodology section, the deterministic LCCA could not adequately evaluate simultaneous variability (Pittenger et al., 2012).

Stochastic LCCA based on bid records

To conduct the stochastic LCCA, the model was developed using commercial simulation software, with each simulation iterated 1000 times, each lasting from 20 s to 55 s. Figure 5-8 shows the output of simulation for double Otta seal.

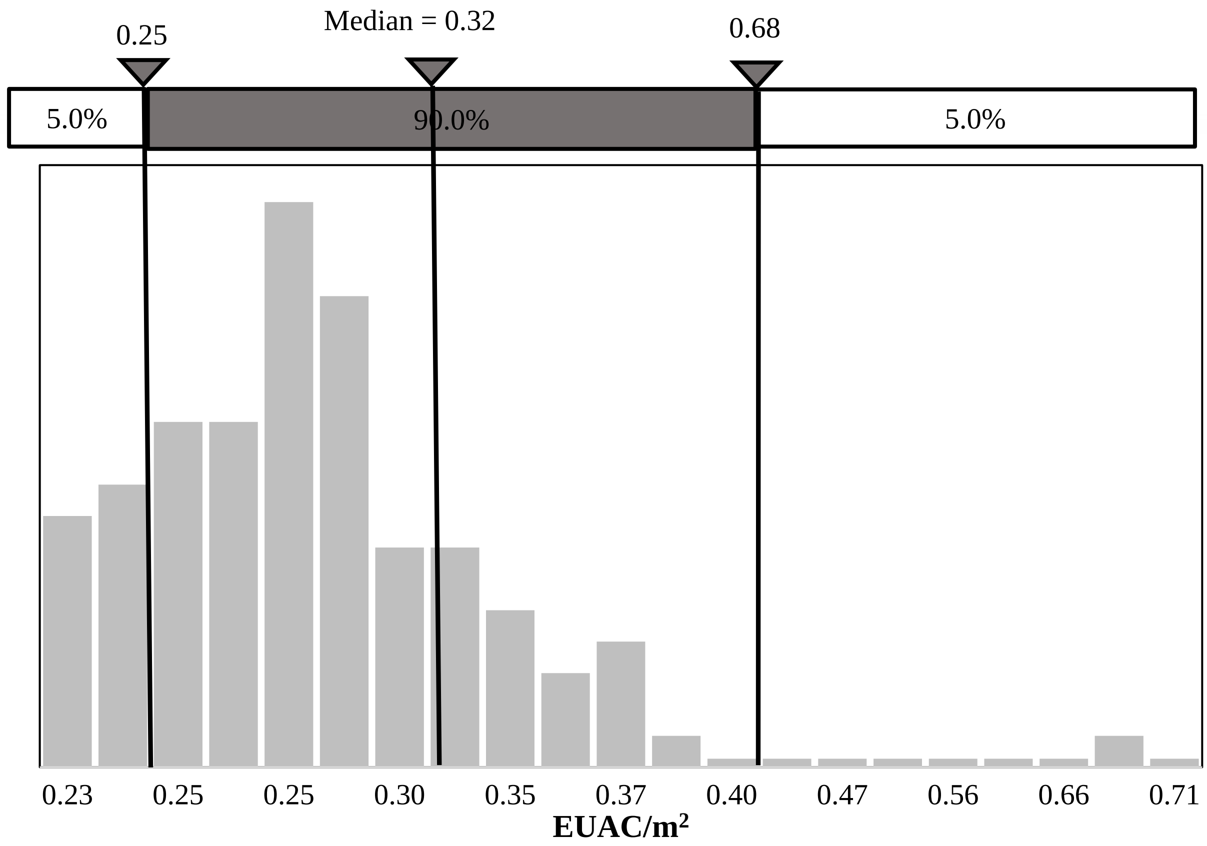


Figure 5-8 Probability distribution function (PDF) for double Otta seal beads on the bid data

The simulation results are summarized in Table 3. The result from running Monte Carlo simulation is a probability density function (PDF) that provides a relative likelihood of EUAC, and PDF variability is represented in Table 4. The standard deviation is an indicator of the amount of dispersion of EUAC values, and for Double Otta seal, the estimate range with a two-tailed 90% confidence interval ranges from 0.25 to 0.33 with a median value of 0.29. The median is a good measure because, regardless of distribution shape, half the values are above the median and half are below the median (Boddy and Smith, 2009). It can once again be seen that among the alternatives double Otta seal has the lower median life cycle cost.

Table 5-3 Result of stochastic life cycle cost analysis (LCCA) based on the bid data

Item	**EUAC (USD/ m^2)** Pavement treatment type Double Otta seal	Double chip seal best fit (Pareto distribution for initial cost)	Double chip seal with using triangular distribution for initial cost	Single chip seal best fit (exact value distribution for initial cost)	Single chip seal with using triangular distribution for initial cost
Median	0.32	0.53	0.55	0.64	0.65
Standard deviation	0.02	0.10	0.07	0.05	0.07
5th percent	0.25	0.41	0.44	0.50	0.53
95th percent	0.40	0.68	0.66	0.79	0.79
Max	0.73	0.79	0.77	0.90	0.84

Stochastic LCCA based on cost breakdown approach

Similar to the previous section, point estimates in deterministic EUAC model were replaced with probability distributions and output was estimated in the quantity variation format. There were 1000 iterations, with simulation times ranging from 18 s to 53 s.

Table 4 shows the simulation outputs. Similar to previous results, it can be seen that once again double Otta seal has a lower median life cycle cost among the alternatives. In addition, for single layer Otta seal, the estimate range with a two-tailed 90% confidence interval ranges from 0.23 to 0.53, with a median value of 0.36, lower than the cost of both double and single chip seal implementations.

Table 5-4 Result of stochastic life cycle cost analysis (LCCA) based on cost breakdown approach

Item	**EUAC (USD/ m^2)**			
	Pavement treatment type			
	Double Otta seal	Single Otta seal	Double chip seal	Single chip seal
Median	0.33	0.36	0.48	0.56
Standard deviation	0.06	0.16	0.14	0.28
5th percent	0.23	0.33	0.32	0.44
95th percent	0.42	0.53	0.61	0.72
Max	0.49	0.64	0.75	0.91

Sensitivity analysis

Another outcome of running a Monte simulation is to determine which among all the input variables has the greatest potential impact on the overall EUAC. As shown in Figure 5-9, the binder cost is in both methods a key factor influencing the EUAC, and it is anticipated that the EUAC would decrease significantly as the binder cost decreases. Another important factor is the sealed layer service life that is directly related to construction quality. This highlights the importance of the construction quality in both sealing methods. As shown in Figure 5-9b, cost of hauling aggregate is the third factor driving variation in the chip seal life-cycle cost, reflecting the fact that the life-cycle cost of chip seal is location dependent. However, since using local aggregate for Otta seal surfacing would be a viable option, transportation is not a key factor affecting EUAC (Figure 5-9b).

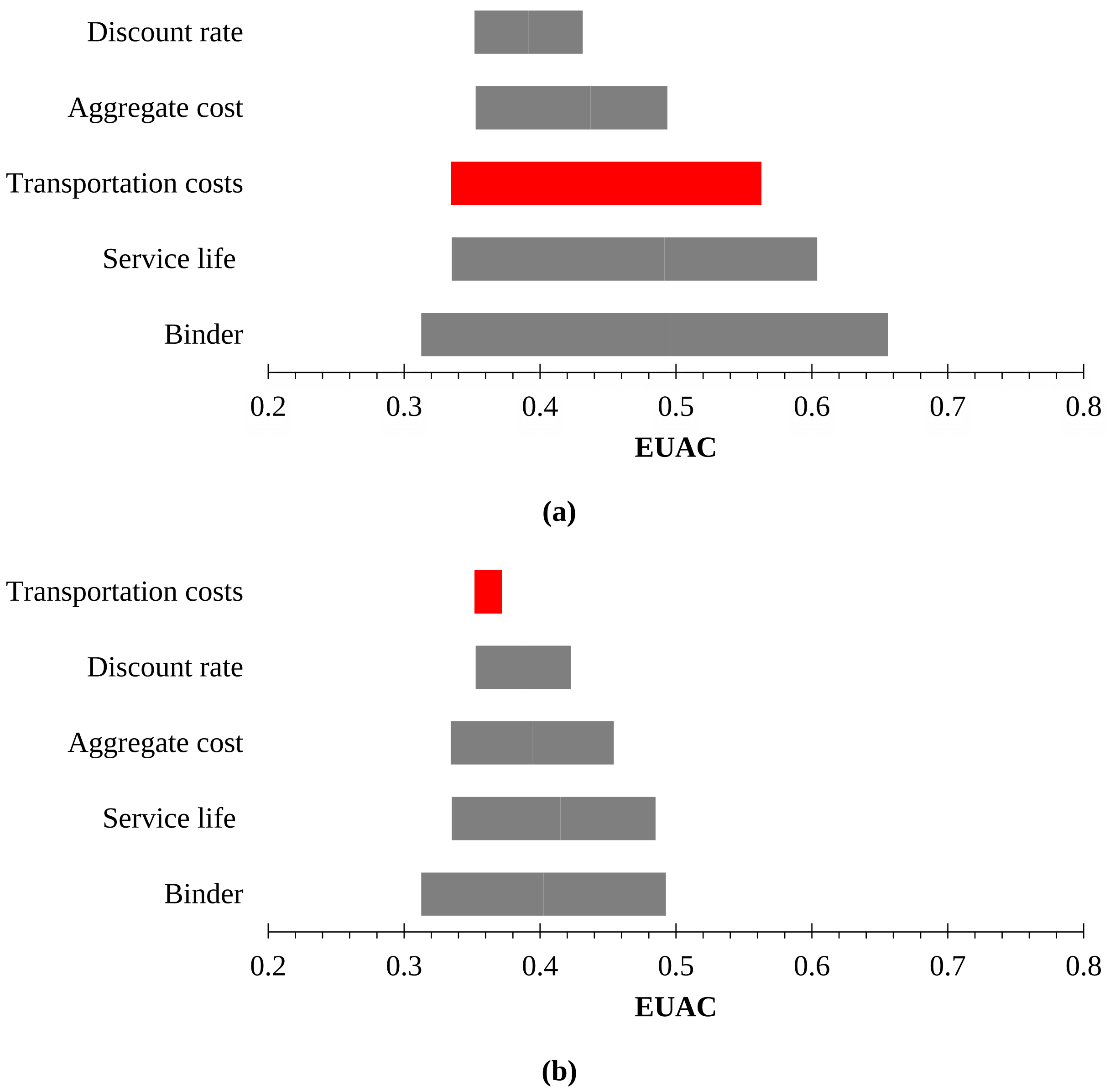


Figure 5-9 Sensitivity analysis results; a) Double chip seal b) Double Otta seal

Summary and Conclusion

This study uses both deterministic and stochastic LCCA approaches to evaluate the economic feasibility of using Otta seal in place of chip seal, with results leading to the conclusion that the use of Otta seal, a technology based on the use of local aggregate, would lead to reduction in transportation and material cost, thereby decreasing total construction costs. Since Otta seal technology is already being used successfully in the state of Minnesota, public agencies might be inclined to use it to reduce the maintenance cost of low-volume roads. However, the inputs can be modified, and the method can be applied to the new inputs in order to produce results that are appropriate for other localities.

Although the analyses results reveal that Otta seal is more cost effective than chip seal, this conclusion is limited only to the State of Minnesota, because the relative unavailability of chip seal aggregate in that state cause transportation cost to be a key factor affecting EUAC for chip seal. In states where high quality aggregate would be locally available, the initial cost of chip seal would probably be significantly reduced. Also, this study was limited to only cost-effectiveness evaluation of Otta seal compared to chip seal and did not investigate the performance aspects of sealed roads. For example, chip seal exhibits relatively higher skid resistance is said to reduce incidence of skid-related accidents (Overby and Pinard, 2013), so Otta seal vs. chip seal is not a crisp choice and depends on agency and user needs.

The methodology followed in this study furnishes agencies with a probability that the preferred alternative will actually produce the lowest life cycle cost, so recommendations that may result from this research project will not only be founded in fundamental LCCA theory but will also provide various public transportation agencies with an added level of confidence in predicting the financial result of pavement treatment alternatives of interest.

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CHAPTER 6. ECONOMICS OF UPGRADING GRAVEL ROADS TO OTTA SEAL SURFACE

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Abstract

Maintenance of low volume roads especially gravel roads is costly, and millions of funding annually are spent for aggregate replacement alone. Otta seal, compared to other bituminous surface treatments (BSTs) for low volume roads that require high-quality materials and specialized expertise, can be constructed using cheaper local aggregates and accessible equipment. However, only three states have reported Otta seal constructions and performance in the US. In this study, an economic analysis was conducted to compare the cost of maintaining a gravel road to the cost of upgrading an existing gravel road to a double Otta seal surface. This analysis was conducted at three levels: deterministic life-cycle cost analysis (LCCA), a stochastic Monte Carlo simulation based LCCA, and a traffic based economic analysis. A generic one-mile rural road in Midwest was considered as a case study location. Although, according to the analysis conducted in this paper, an upgrade to Otta seal investment might be justified by maintenance savings, resorting to only such justification cannot warrant investment in most cases. The upgrade from gravel road to Otta seal, or any other BSTs, might be justified in terms of enhancing safety for road users and also encouraging economic development beneficial to local areas.

Keywords: Otta seal; gravel road; bituminous surface treatment; traffic-based life-cycle cost; Monte Carlo simulation.

Introduction

Federal funding has been allocated and spent focusing more on new infrastructure construction rather than promoting and maintaining existing infrastructure (Amoaning-yankson and Amekudzi-kennedy, 2017). The state and local governments have jurisdiction over almost 97 percent of all roadways in the US. From 1953 until now, the total road and street mileage has increased about 18.3 percent, and paved mileage has increased by 183 percent (Federal Highway Administration, 2014). Since much of the required infrastructure is already in place, achieving better value from current roads should be prioritized. According to a Federal Highway Agency (FHWA) 2016 budget estimate, "the percentage of funding applied to new construction is decreasing while funds for rehabilitation of the system are increasing"(FHWA, 2015).

With the reduction in building new roads, while further deterioration of the existing system is anticipated if current policies are continued (Huntington and Ksaibati, 2011; Weingroff, 2013), current infrastructure systems can be maintained in a cost-efficient manner by a preventive maintenance program (Federal Highway Administration, 2014). Preventive pavement maintenance is defined as "a program strategy to arrest light deterioration, retard progressive failures, and reduce the need for routine maintenance and service activities" (FHWA, 2007). The objective of such strategies is to increase the service pavement service life by applying treatments before its deterioration. An effective pavement preservation strategy is comprised of a series of different treatments (Bozorgzad, 2018; Bozorgzad and Lee, 2017; Geoffroy, 1996; Ghalesari and Rasouli, 2014; Gransberg and Scheepbouwer, 2010; Nemati and Dave, 2018; Skorsetch et al., 2015). Seal coatings are one relatively inexpensive type of treatment that can provide a protective wearing surface on the existing pavement surface to increase service life.

During the early 1960s, a significant portion of the total public road network in Norway was comprised of unpaved gravel roads with low bearing capacity and carrying an annual average daily traffic (AADT) of 50-400 vehicles (Overby and Pinard, 2007). With the arrival of the spring thaw period, the roadbeds softened, and many road sections became impassable for vehicles, irrespective of weight. Considering the prevailing practices at that time, these road sections would normally have required reconstructions before bituminous surfacing was applied (Overby and Pinard, 2007; Pinard, 2013). However, it was reported that the road rehabilitation program actually progressed slowly because of budgetary constraints and difficulties associated with setting up heavy construction plants (Overby and Pinard, 2013) . In 1963, this situation led to a need for developing a faster method/treatment that could improve the quality of gravel roads at relatively lower cost (Overby and Pinard, 2007). The Norwegian road authorities desired that such a surface treatment be cost-effective to provide a faster return on investment, perform (as perceived by the road user) in a manner similar to conventional bituminous surfacing, and comply with the following requirements (Overby and Pinard, 2012):

- Be cheap and easy to implement;
- Utilize locally-available aggregates;
- Be impervious to prevent water incursion into moisture-susceptible base materials;
- Be very flexible, durable, and easy to maintain.

Initial field trials of such a bituminous surface treatment were carried out during 1963–1965 in the Otta Valley, Norway, which was named Otta seal later (Overbay, 1999). Although Otta seal was originally intended to be used only as a temporary bituminous surfacing for unpaved gravel roads with low traffic volume, its good performance resulted in being employed as a useful surfacing technique for both newly-constructed and existing asphalt roads and for both low and medium traffic situations. From 1965 until 1985, more than 12,000 km of unpaved roads, constituting approximately 20% of the total Norwegian road network have been surfaced using

Otta seal. Although there has been a rapidly increasing number of Otta seal surface treatment in Nordic countries, Asia, Africa, New Zealand, and South America (Kelly and Juma, 2015), its use in the U.S. is currently rather limited due to a lack of knowledge and of the empirical design approach associated with this technique that requires economic analysis and evaluation of trials or demonstrations before employment. Minnesota, Iowa, and South Dakota are the only three states that have currently completed Otta seal projects in the North America (Ceylan et al., 2018; Gushgari et al., 2018; Johnson, 2003).

There were efforts to compare life-cycle cost of double Otta seal with conventional hot mix asphalt (HMA) (Perveneckas et al. 2013, Vaitkus et al. 2018). The result of a previous studies conducted in Lithuania showed that use of double Otta seal for low volume roads can reduce the maintenance life cycle cost up to 44% (Perveneckas et al. 2013) (note that the maintenance cost was not included in the aforementioned analysis). In addition, another study have reported Otta seal's lower life-cycle costs compared to other bituminous surface treatments (BSTs) (Overby and Pinard 2013). However, economic evaluation of upgrading a gravel road to Otta seal surface was not conducted before. To this end, providing insights on life-cycle cost of gravel road juxtaposed with those of double Otta seal would be helpful for U.S secondary road authority and agencies to make informed decisions regarding their low volume road preservation activities. Given a fact that the U.S. has approximately 1,417,000 miles of unpaved secondary roads that experience relatively low daily traffic volume (Jahren et al. 2005).

In this paper, the life cycle cost of surfacing and maintaining an upgraded gravel road to an Otta seal coated surface over a one-mile generic road in Midwest was evaluated through deterministic and stochastic life-cycle cost (LCCA) analyses. Various road and highway agencies in Minnesota and Iowa, who have implemented Otta seal, provided access to the historical cost records that helped to conduct this study. Previous studies have also shown that annual maintenance costs for a gravel road increases as the AADT increases (Skorsetch et al., 2015). Moreover, because there is a general trend toward increasing traffic volume, especially in urban areas, further studies were recommended to determine the appropriate times for upgrading roads to surfaces with BST considering traffic volume (Jahren et al., 2005). Therefore, in the second part of this study, a traffic volume-based economic analysis was conducted based on the data obtained from multiple gravel roads in four counties in (i.e. Goodhue, Winona, Buchanan, and Cherokee) in Minnesota and Iowa, exhibiting different annual daily traffic (ADT) and AADT patterns to evaluate cost-per-mile trends for gravel roads as traffic increases.

Overall descriptions of analysis approach

FHWA describes life-cycle cost analysis (LCCA) for highway projects as “an analysis technique to evaluate the overall long-term economic efficiency between competing alternative investment options” (Federal Highway Administration, 2017). The basic model outlined by FHWA was used to conduct the LCCA for this study (Federal Highway Administration, 2017). In addition to the FHWA life-cycle cost analysis approach, a stochastic analysis was also employed to compare competing design alternatives. The specific approach for this study utilizes equivalent uniform annual cost (EUAC) analysis, permitting elimination of many assumptions required when using the more common, and more problematic, net present worth LCCA (Liedtke and Scholz, 2009; Walls III and Smith. R, 1998). Deterministic EUAC, the traditional method used for decision-making in pavement management involves using point estimates that result in a single output value (Almeida et al., 2015; Batioja-alvarez et al., 2018; Bozorgzad and Lee, 2017; El-din and Kim, 2017; Fathi et al., 2018; Kim and Bozorgzad, 2018; Lee Jr., 2002; Nahvi et al., 2019; Rahman and Vanier, 2004). The outcome of a deterministic LCCA depends on numerous estimates, forecasts, assumptions, and approximations, with each factor having some potential to introduce errors into the results. The role such errors, in affecting the outcome of the EUAC, must be known to a decision-maker if informed decisions are to be made with confidence. Moreover, the degree of uncertainty associated with each alternative is itself a factor to be considered when selecting among competing alternatives (Amini et al., 2012; Anand et al., 2017; Gransberg and Scheepbouwer, 2010; Nahvi et al., 2018b, 2018a; Salem et al., 2003; Shahata and Zayed, 2013; Sritharan, 2017; Walls III and Smith. R, 1998). Figure 6-1 shows different components of the economic analysis framework considered in this study.

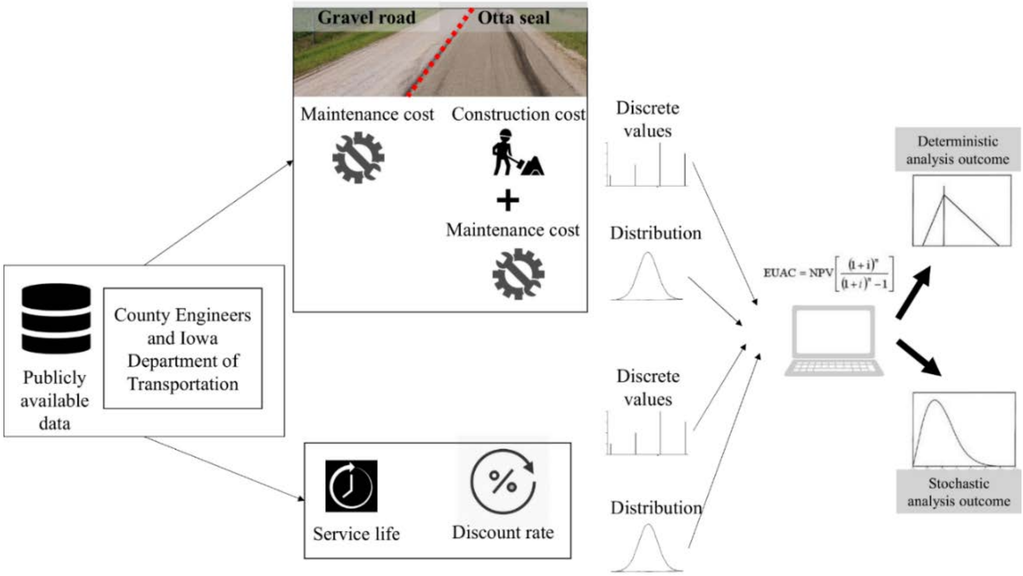


Figure 6-1 Economic analysis framework

In this paper, one mile of a generic unpaved road in Midwest was considered as a case study. As it is shown in Figure 6-1, different costs associated with Otta seal and gravel roads were estimated. To address the issues related to a deterministic EUAC model (e.g. sensitivity to discount rate or volatility of underlying commodity prices), a stochastic life-cycle cost model was also employed. Such an approach allows input variables to range across their more recent historic variations utilizing a Monte Carlo Simulation (MCS) (Reigle and Zaniewski, 2002; Tighe, 2001).

Initial and maintenance cost estimations

Although there have been previous attempts to use historical gravel road maintenance cost analysis for low-volume roads in Minnesota, historical cost analysis in Minnesota reveals inaccuracies in data recorded by field crews, as data in many cases not recorded in proper categories (Jahren et al., 2005). Since "Maintenance activities for bituminous roads were sometimes charged to gravel roads and vice versa" (Jahren et al., 2005), a methodology that estimates the cost of surfacing and maintaining gravel roads was adapted, and this has turned out to be useful when requirements for labor, equipment, and materials cannot be accurately predicted based on historical analysis (Jahren et al., 2005). Available bid records were also used to estimate costs of double Otta seal implementations.

Gravel road

Cost estimation in this study assumed the roadway cross-section as shown in Figure 6-2.

Figure 6-2 Gravel road cross section used in the analysis (photo taken on September 23, 2017, at Cherokee County, IA, U.S.A.)

Assumptions were made in performing such estimations for graveling a one-mile road and maintaining the gravel surface, and calculations were based on methods described in the Caterpillar performance handbook (Caterpillar, 2015). The set of assumptions used in cost estimation were:

- A one-mile (1.6 km) roadway with a 24-foot (7.3 m) wide top;
- 2 inches (5 cm) of new gravel assumed for graveling/ re-graveling (400 yd^3/mile or 400 ton/mile);
- Gravel cost was approximately \$10.00/yd^3;
- Motor grader cost was 60 USD/hr (including fuel);
- During grading operations, the motor grader traveled at an average speed of 4 mph (6.5 km/hr);
- A 12-foot moldboard with a carry angle of 60 degrees was used;
- 3 motor grader passes per mile were needed;
- Trucks (with twelve-yard capacity) cost 50 USD/hr (includes fuel);
- Operator cost of 40 USD/hr (a round trip for each aggregate load would take 75 minutes).

Based on discussions with involved county engineers, it was found that number of grading operations could vary from three times per month to three times per week, depending on daily traffic volume. In addition, grading months during any given year could vary from one region to another, depending on severity of snow events and snowfall rates. Because of such uncertainties associated with the number of grading operations, this parameter was plugged into the stochastic analysis as one of the uncertain input variables.

To develop an estimate of labor and equipment cost, calculation of hourly operating area was necessary. The Caterpillar performance handbook (Caterpillar, 2015) suggests the following Equation for hourly operating area estimation:

$$A = S \times (l_e - l_o) \times 5280 \times E \tag{1}$$

Where A is an hourly operation area, S is the operation speed (mph/hr), L_e is the effective blade length (10.4 ft-3.2 m), L_o is the width of overlap (2.4 ft- 0.75 m), and E is the job efficiency (0.75). The hourly operating area(A) for these assumed values based on the calculation from Equation (1) turned out to be $126.720\ ft^2/hr$.

Using this hourly operating area value, the time to blade a one-mile road can be calculated using Equation (2).

$$t = \frac{Surface\ area}{Motorgrader\ rate} = \frac{24\ ft \times 5280\ ft\ (1\ mile)}{126.720\ ft^2/hr} = 1\ hr \tag{2}$$

Since the time to blade a one-mile road is one hour, a grading machine can cover three passes in an hour (taking into account an assumed efficiency factor of 0.75). Based on time-to-blade calculations, the time per year spent on a one-mile roadway can be calculated using Equation (3). Since the number of required grading operations each year is quite uncertain, a numeric value was not assigned to this variable.

$$T = 1.00 \frac{hr}{mile} \times N\ miles \tag{3}$$

After the annual time spent on a one-mile roadway is determined, surfacing and maintaining (grading) costs can be calculated, with calculations for labor and equipment costs of surfacing (graveling) given by the following Equations (4-7).

$$Number\ of\ gravel\ loads\ needed\ for\ one\ mile\ road = \left({}^{1\ load}/_{12\ yd^3}\right) \times \left({}^{1000\ yd^3}/_{mile}\right) \approx 84 \tag{4}$$

$$Equipment\ cost = 84 \times 1.25\ hrs\ (time\ to\ load\ material) \times 60\ \left(\frac{USD}{hr}\right) = 6{,}300\ USD \tag{5}$$

$$Labor\ cost = 84 \times 1.25\ hrs\ (time\ to\ load\ material)\ \times 40\left(\frac{USD}{hr}\right) = 4{,}200\ USD \tag{6}$$

$$Material = Gravel\ unit\ cost\ \left(\frac{10\ USD}{yd^3}\right) \times \left(\frac{1000\ yd^3}{mile}\right) = 10{,}000\ \left(\frac{USD}{Mile}\right) \tag{7}$$

Otta seal

The initial construction cost of a one-mile double Otta seal was obtained from publicly-available Minnesota and Iowa bid tabs (“Bid Letting,” n.d.). The data set used in this analysis contained three bid records obtained over the previous two-year period, as shown in Table 1. Note that only surface treatment cost was considered in the economic analysis, and non-related costs (e.g. miscellaneous, pipes and aprons, extensions, sub-drain, etc.) were not included. From reviews of county cost data analysis (Jahren et al., 2005), the annual average maintenance expenditure for bituminous roads was assumed to be 2,400 USD/mile (adjusted using the price trend index for Iowa highway constructions for the year of 2017).

Table 6-1 Costs for double Otta seal projects over the past two years

Project location	Year	Double Otta seal cots (USD/mile)
CSAH 2, Winona county, MN	2016	57,000
CSAH 13, Winona county, MN	2016	67,600
CRs 31, 37 and 116, Winona county, MN	2017	59,800
L-40, Cherokee County, IA	2018	64,500

When upgrading a gravel road to a BST road, the cost of some maintenance activities may change. For example, activities like grading, graveling, and coating with dust suppressants would be eliminated, while the cost of snow-removal operations on a paved road would be higher because more time is spent on snow plowing.

Since snow and ice removal adds major costs to the maintenance of bitumen treated roads, this factor was included in the economic analysis. The following assumptions were made in estimating additional cost of snow removal activities:

- Snow removal operation would be initiated when there is approximately one inch of snow accumulation on the road surface;
- On an Otta seal road, two snowplow passes would be enough to clear the surface.

Snow-removal driving costs per-mile were obtained from a MnDOT highway fund expenditure report for 2017 (Minnesota Department of Transportation, 2017) (Figure 6-3(a)). Note that costs were adjusted to a 2017-dollar value, assuming a 3 percent annual inflation factor, based on historic MnDOT maintenance and operations commodity and labor inflation. In addition, the number of snow events with accumulated snowfall rates of at least one inch over the last 30 years were determined by an automated surface observation system (ASOS, 2018) and are shown in Figure 6-3(b).

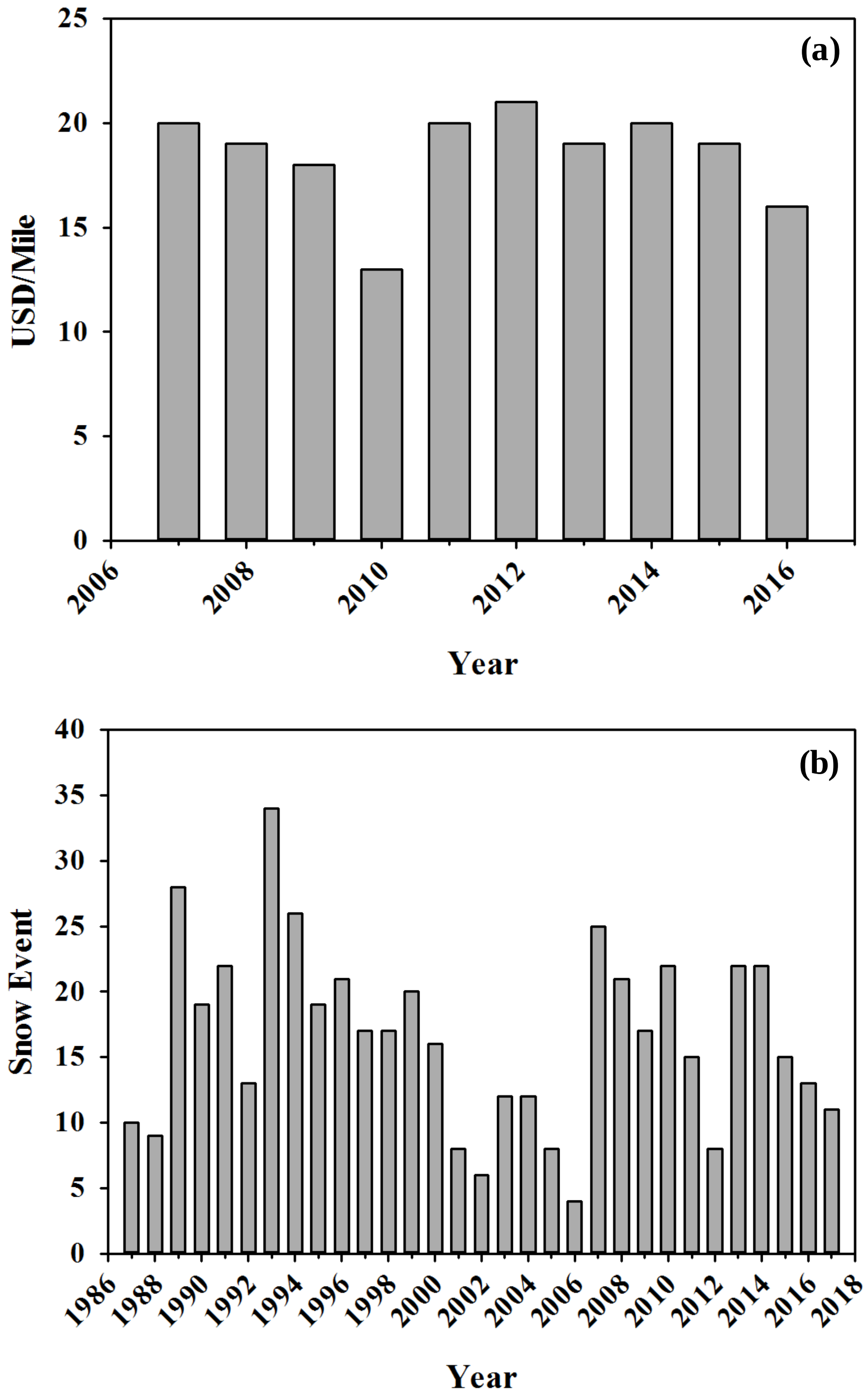


Figure 6-3 Information used to estimate snow removal operation; (a) snow removal driven cost per mile; (b) number of snow events with one more than one-inch snow falls

The average number of snow events and snow removal driving costs per mile were used in the LCCA, with snow removal annual cost calculated through Equation (8).

$$\mathit{Snow\ removal\ average\ annula\ cost} = \mathit{Average\ number\ of\ snow\ events} \times \mathit{Avergae\ snow\ removal\ driving\ cost}\ \left(\frac{USD}{mile}\right) \times 2\ \text{(two passes of snowplow)} = 17 \times 19\ \left(\frac{USD}{mile}\right) \times 2 \approx\ 650\ USD \tag{8}$$

Economic analysis

The economic analysis given in this study can be adjusted by local authorities to reflect the typical costs and timing of various situations. The specific approach used in this study applied EUAC analysis, thereby eliminating many assumptions required by the more common net present worth LCCA (Walls III and Smith. R, 1998). Similar to discussion provided in previous section, the issues associated with a deterministic EUAC model, such as sensitivity to discount rate or volatility of underlying commodity prices, were addressed by developing an MCS based economic analysis. In addition, for the stochastic LCCA approach, previous twenty-year discount rate data from the Federal Reserve (Federal Rserve, 2018) was obtained and included in the model.

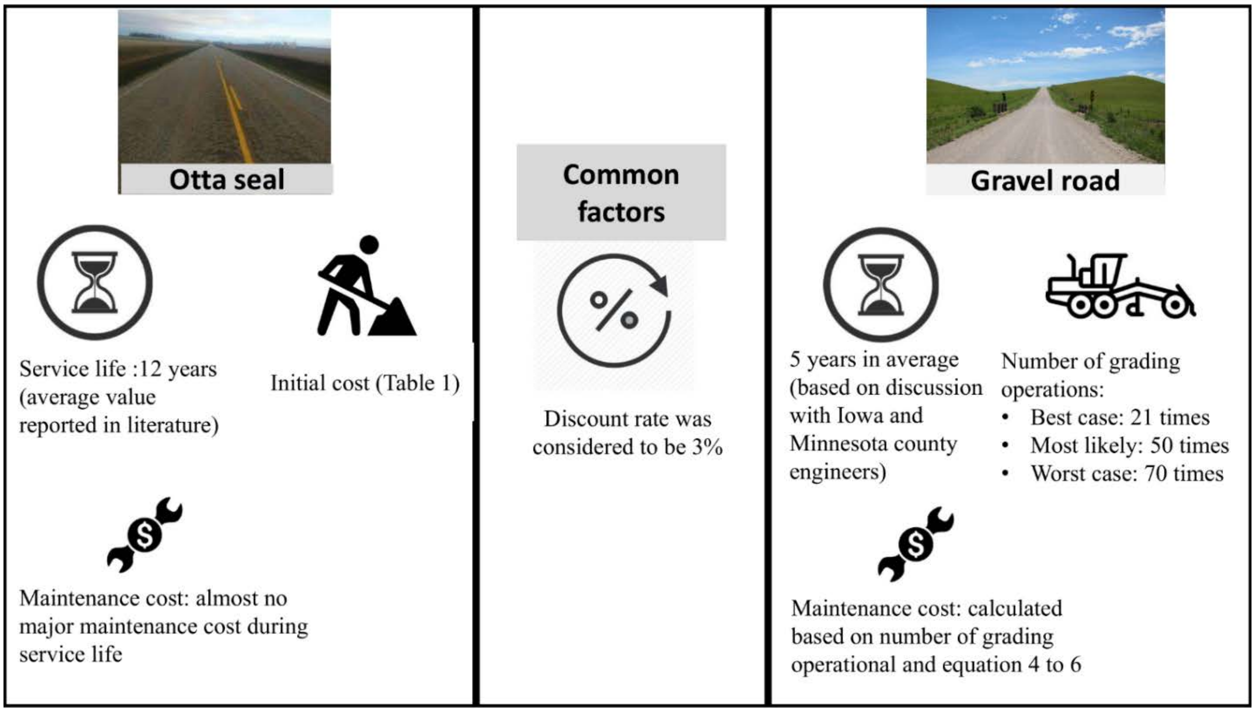
Deterministic LCCA

As it is shown in Figure 6-4, the following assumptions were made in performing the deterministic LCCA for a one-mile road treated with double Otta seal and gravel.

- The design service lives of new graveled and new double Otta seal roads would be 5 and 12 years, respectively.
- In accordance with the FHWA technical bulletin, a discount rate of 3% was used (FHWA Pavement Division, 1998).
- A sensitivity analysis was performed with respect to the number of grading operations. The following three possible scenarios for determining the number of grading operations were evaluated.

  - Low value: The road is graded 3 times per month from April to October, a total of 21 times.
  - Most likely value: The road is graded 5 times per month from March to November, a total of 50 times.
  - High value: The road is graded 7 times per month from March to November, a total of 70 times.

- Because the study is oriented toward low-volume roads, the ADT is low that user costs associated with traffic disruption during construction and maintenance operations would be trivial, so they are eliminated from the model.



Service life :12 years (average value reported in literature)

Initial cost (Table 1)

Maintenance cost: almost no major maintenance cost during service life

Discount rate was considered to be 3%

5 years in average (based on discussion with Iowa and Minnesota county engineers)

Number of grading operations:
- Best case: 21 times
- Most likely: 50 times
- Worst case: 70 times

Maintenance cost: calculated based on number of grading operational and equation 4 to 6

Figure 6-4 Summary of inputs used for determinist economic analysis

Table 6-2 shows the LCCA outputs in equivalent uniform annual cost format. As shown in Table 2, the gravel road maintenance cost varied from almost 1,500 USD to 5,000 USD depending on the number of grading operations. In addition, the average additional annual life-cycle cost for agencies and counties to upgrade a one-mile gravel road to a one-mile double Otta seal surface was estimated by subtracting Otta seal EUAC (USD/mile) and Gravel road EUAC (USD/mile). As exhibited in Table 6-2, the average additional annual cost for upgrading a one-mile gravel road to a one-mile double Otta seal surface road would vary from nearly 2,500 USD to 5,000 USD based on gravel road annual maintenance costs.

Table 6-2 LCCA outputs in equivalent uniform annual cost format

Item	Low value	Most likely value	High value
Number of grading operations (during seven months)	21	50	70
Gravel road maintenance cost (USD/ mile)	1,470	3,500	4,900
Double Otta seal cost (USD/mile)	57,000	59,800	67,600
Otta seal EUAC (USD/mile)	10,220	10,575	11,550
Gravel road EUAC (USD/mile)	5,500	7,530	8,930
The average additional annual cost to upgrade a one-mile gravel road to a one-mile double Otta (USD/mile)	4,720	3,045	2,620

Stochastic LCCA

Goodness-of-fit tests using Komogorov–Smirnov (K–S), Anderson–Darling (A–D) and Chi-squared tests were conducted to determine a well fit distribution for total rehabilitation and mainline roadway costs, and the final fit distributions were then used to perform an MCS for a probabilistic LCCA to demonstrate the value of using the proposed approach. The probability distributions were directly incorporated into spreadsheet using the software "@risk". An MCS uses the defined distribution to cover all possible outcomes to calculate the life cycle costs (LCC) for each scenario. In addition, MCS estimates the probability associate with the calculated LCC. Because of the fluctuating number of grading operations, that variable was treated probabilistically in stochastic EUAC calculations. To describe its uncertain nature, a triangular distribution for this number was used in the model, following the same scenarios developed in the deterministic analysis section. Costs associated with traffic control during construction and maintenance were also not considered in this study. Figure 6-5 shows the primary costs for maintaining a gravel road, including grading and resurfacing for a five-year re-graveling cycle. Similar to gravel road EUAC calculations, maintenance was treated deterministically for Otta seal LCCA. Based on bid records from Minnesota and Iowa, a triangular distribution was used to describe the construction cost of double Otta seal, and costs associated with traffic control during construction and maintenance were not considered. Service-life uncertainty creates sensitivity in EUAC results (Peshkin, D. et al., 2004), making it a good candidate for stochastic analysis.

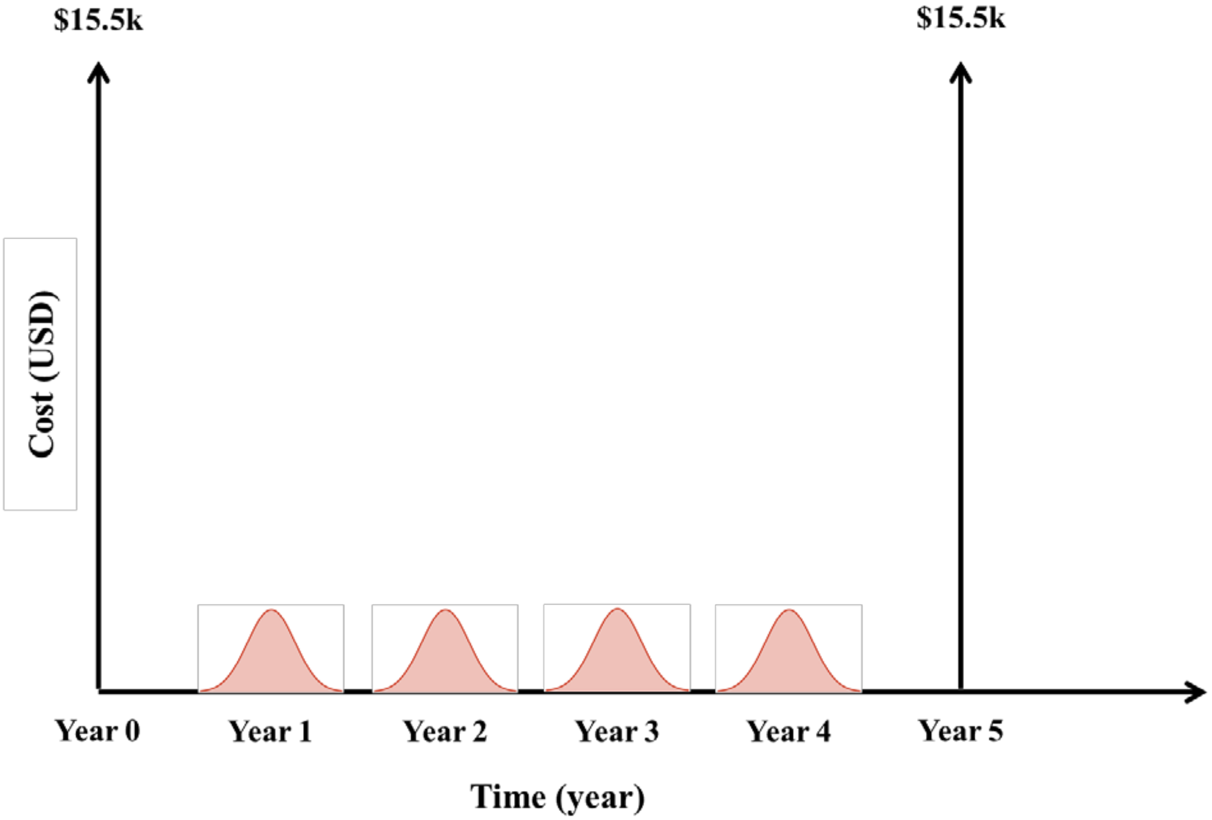


Figure 6-5 Maintaining and surfacing costs for a five-year time windo

According to the literature and discussion with Minnesota county engineers, likely service life of a double Otta seal road would be between nine to fifteen years (Figure 6-6) (Johnson, 2011; Overbay, 1999; Overby and Pinard, 2013, 2007, 2012).

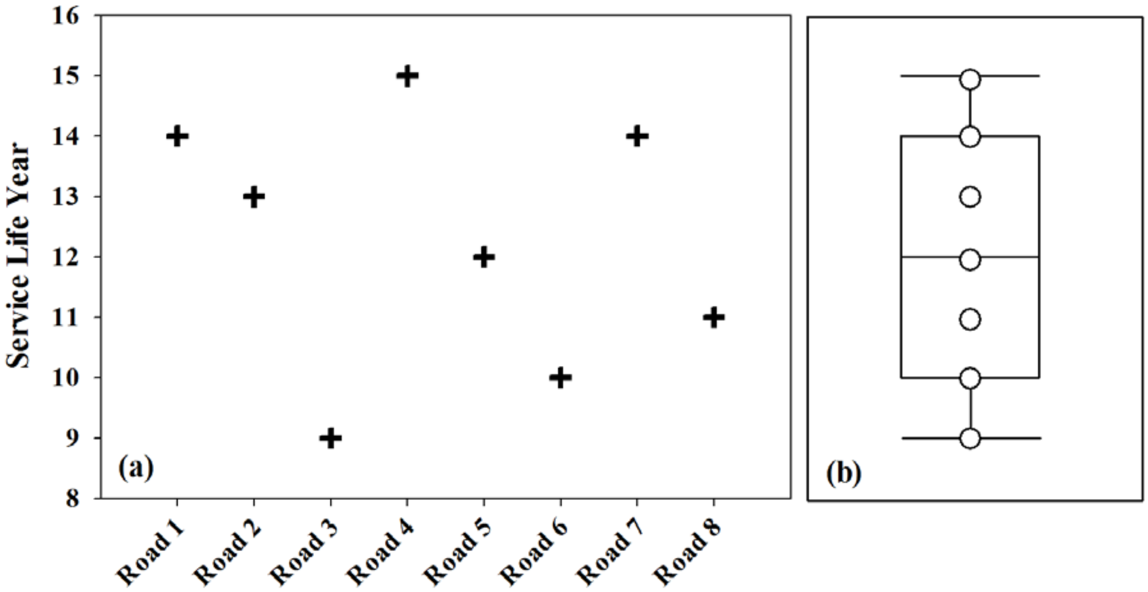


Figure 6-6 Typical Otta seal service life in years; (a) data obtained from sit visits; (b) range mentioned in the literature (Johnson 2003, Overby and Pinard 2007, 2012, 2013, Ceylan et al. 2018, Gushgari et al. 2018)

In addition to the literature review, many site visits were conducted to explore the longevity of Otta seal roads. The results of these visits presented that double Otta seal's service life was within the range described in the literature. Table 6-3 summarizes the visited site sections indicating roads locations, current condition of the visited site sections, and the construction years.

Table 6-3 Summary of visited site sections

Road	**County or City**	**Const. Year**	**ADT**	**Performance**
Trial section	St. Louis County	2000	260	Potholes and wash boarding problems due to uniform aggregate application
CR 73	Wabash County	2003	Wabash County	Good condition
CR 168	Cass County	2001	Less than 150	Good condition
Unmarked road	Cass County: Northeast of CR 168	2001	Less than 150	Good condition
CR 171	Cass County	2001	Less than 150	Good condition; Thermal cracks had occurred at intervals of 50 ft
CR 25	Cass County	2001	Less than 150	Good condition; Thermal cracks had occurred

To conduct the stochastic LCCA, an MCS based model was developed, and each simulation with times ranging from 20 s to 55 s was iterated 100,000 times. Figure 6-7 shows the EUAC results for both double Otta seal and gravel roads throughout their life cycles. As shown in the Figure 6-7, upgrading a one-mile gravel road to double Otta seal would require an average of 2,400 USD in annual expenditures. Figure 6-7 also indicates that in nearly 20% of various possible scenarios, surfacing a road with double Otta seal might incur the same costs as those for gravel roads. Previous studies have shown that annual maintenance cost for a gravel road increases as the annual average ADT increases (Skorsetch et al., 2015). Since there is a general trend toward increasing traffic volume, especially in urban areas, it was recommended that further studies be conducted to determine the best times for upgrading gravel roads to BST surfaces taking traffic volume into consideration (Skorsetch et al., 2015).

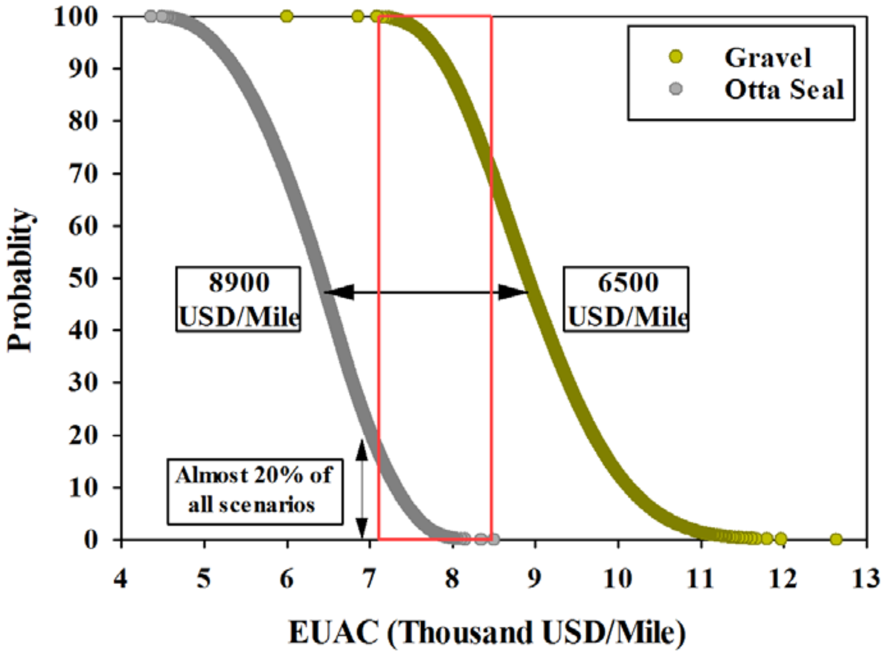


Figure 6-7 Stochastic LCCA results; double Otta seal versus gravel road

Traffic volume based economic analysis

To study the impact of traffic on annual maintenance cost of gravel roads, a detailed questionnaire was developed for this purpose and sent to some Minnesota and Iowa county engineering offices who had experienced similar climatic and traffic conditions. This survey included detailed questions about items such as gravel road service life and graveling and grading frequency under different traffic conditions. Figure 6-8 presents a summary of key findings obtained through both surveys and interviews.

An important factor considered in the surveys was AADT, as presented in the format of percentage of ADT in Figure 6-8. According to AASHTO (Kawa et al., 1998), a single heavy truck would impose more damage on a pavement than many other vehicles with standard 18-kip load equivalence. As shown in Figure 6-8, when traffic volume increases, gravel road service life along with frequency of grading and graveling decreases. The collected data show that increasing truck traffic will result in both an increase in graveling frequency and a decrease in service life.

An economic analysis was employed to compare the annual maintenance costs of maintaining gravel roads under different traffic volume and truck traffic scenarios. Unlike what was observed in previous section, the degree of uncertainty associated with grading frequency and gravel road service life are not significant, and discrete values can be used to describe these two factors. Determinate life cycle cost analysis was then used to assist in making decisions as to whether or not to upgrade a gravel road to one with an Otta seal surface. The analysis was conducted using the same assumptions which were discussed in details and used in the previous section, with the results shown in Figure 6-9.

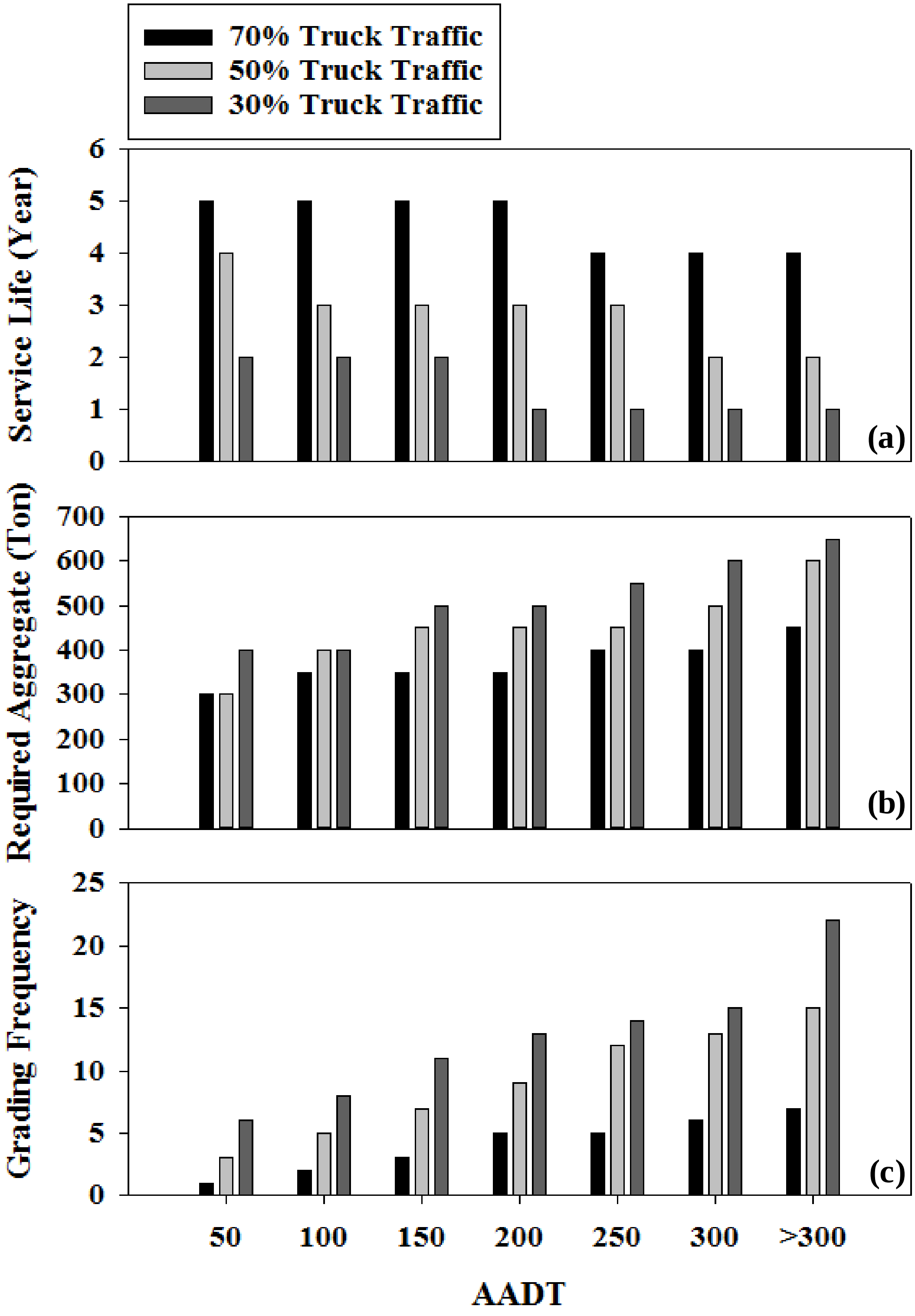


Figure 6-8 Summary of interviews and surveys; (a) impact of traffic on service life; (b) impact of traffic on amount of required gravel for surfacing; (c) impact of traffic on grading frequency

As mentioned before there are many advantages associated with using bituminous surface treatment on a gravel road such as dust control and significant improve in ride quality. Therefore, when both Otta seal surface and gravel road incurred the same cost, using gravel road is not reasonable. At this end, a maximum Otta seal annual maintenance cost value of 12,000 USD (see Figure 6-9) was taken as the economic criterion. Figure 6-9 indicates that gravel roads with high truck traffic and ADT over 200 are good gravel road candidates for upgrading to Otta seal roads. The approximate percentages of miles of gravel for both categories (economic and non-economic) are shown in Figure 6-9, where it can be seen that there are few miles of gravel road in the high traffic volume category. In addition, since all the low-truck-traffic gravel roads are in the non-economic category, it may not be possible to justify Otta seal surfacing based solely on economic analysis for those gravel roads.

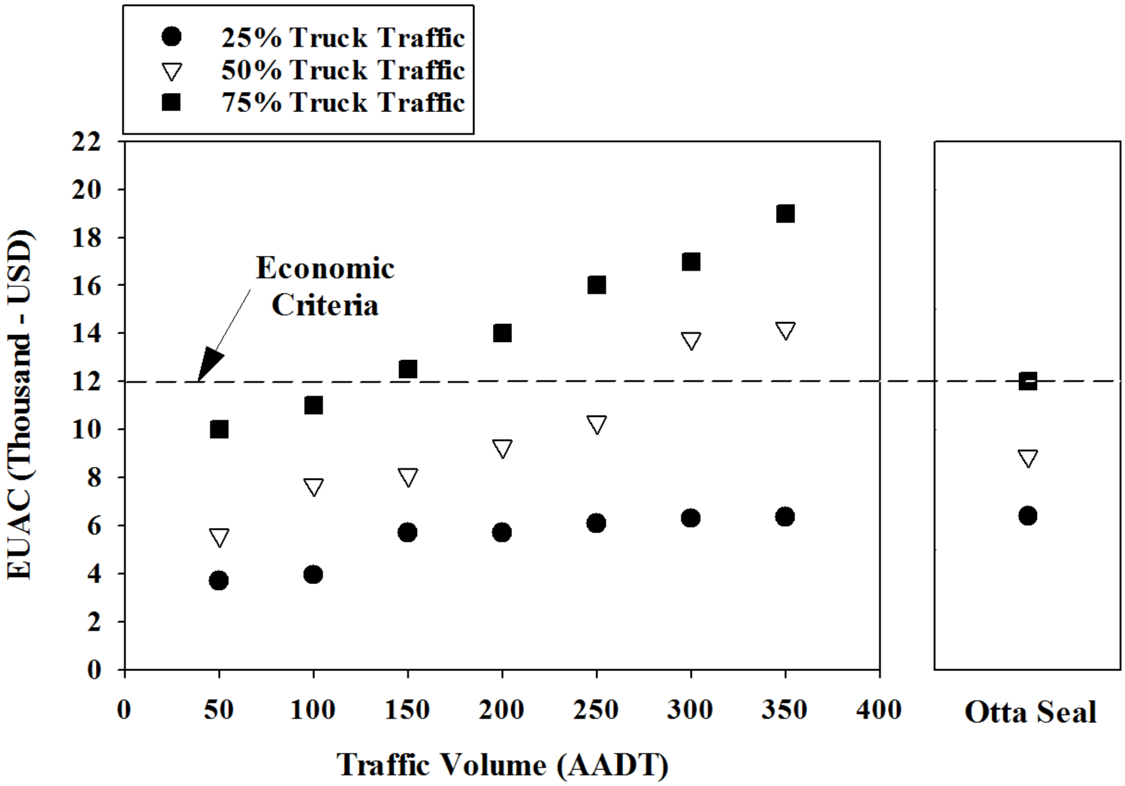


Figure 6-9 Results of traffic volume based economic analysis

Indirect benefits of Otta seal over gravel road

It may not be possible to justify roadway surfacing decisions based solely on economic analysis, because there are many benefits associated with BSTs on a gravel road that cannot be expressed in terms of monetary value. Several of these benefits, such as safer surfaces, improved driving efficiency, and dust control, cannot be quantified and included in an economic analysis. BST implementation on a gravel road would create a surface with higher skid resistance, and unlike that for a loose gravel road, driving efficiency increases when a vehicle moves on a smooth hard surface. Driving on a gravel road also creates a rougher ride and increases wear and tear on a vehicle's tires and undercarriage, and less dust accumulated in car filters would result in greater fuel efficiency and reduced maintenance costs (Frissell and Trombulak, 2000). Since BSTs, especially Otta seal, provide dust-free surface for drivers and residents, living conditions would improve. Dust-free surface provided by Otta seal possibly reduces health-related breathing issues, decreases water and other environmental pollution, and also improves cleanliness for adjoining landowners.

Conclusions

The principal objectives of this study were to evaluate the feasibility of Otta seal implementation as an alternative surface treatment for low-volume roads and to evaluate the cost-effectiveness and performance of Otta seal compared to traditional bituminous seal coat surfaces in terms of maintenance of gravel roads. The conclusions drawn from this study can be summarized as follows.

- Stochastic and deterministic economic analyses were conducted to determine the investment needed to upgrade a gravel road to an Otta seal road. Since historical bid and performance records of Otta seal in Iowa were not available, a generic one-mile road in Midwest was investigated as a case study for conducting the analysis.

- Although the results of the economic analysis revealed that in some cases an upgrade to Otta seal might be justified by maintenance savings alone, the analysis showed that maintenance savings alone in most cases do not provide good justification for the investment.
- Another economic analysis was conducted to determine the appropriate times for upgrading gravel road to surfaces covered with BSTs, taking traffic volume into consideration for low volume roads in Midwest with results revealing that, for 15% of gravel roads, it might be possible to justify Otta seal surfacing based solely on economic analysis.

Since the methodology followed in this study provides agencies with a probability that the preferred alternative actually produces the lowest life cycle cost, recommendations that may result from this research are not only established in fundamental LCCA theory but can also provide public transportation agencies with an added level of confidence in predicting the financial results of pavement treatment alternatives.

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Disclosure statement

No potential conflict of interest was reported by the authors.

Additional information on data collection

This section provides additional information that was not published in the journal article on the data collection approach and the interviews conducted in this study. To study the impact of traffic on the annual maintenance cost of gravel roads, a questionnaire was developed for this purpose and sent to some Minnesota and Iowa county engineer offices that have similar climatic and traffic conditions. This survey included questions about items such as gravel road service life and graveling and grading frequency under various traffic conditions. In addition, the same questions were used to conduct interview with some of the motor graders operators (who maintain gravel roads; informally called “blade operators”) in State of Iowa.

Both surveys and interviews were consisting of three technical questions on:

- Impact of traffic on service life of unpaved roads
- Impact of traffic on amount of required gravel (or other surfacing materials) that must be added in order to maintain the road properly
- Impact of traffic on grading frequency

Three county engineers and eleven motor grader operators participated as survey repondents in this study. All of the respondents had eight to twenty-five years of experience with maintenance of low volume roads.

The interviews were conducted individually, and each interview took between ten and fifteen minutes. In addition, that there were negligible variations regarding the ranges of answers provided by the respondents for all the three questions. The result of the survey were shown in Figure 6 through 8.

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CHAPTER 7. GENERAL CONCLUSION

Presently, there is an expanding interest among transportation agencies and state Departments of Transportation to use data-driven decision-making tools for overcoming economic issues in infrastructure related projects. The objective is to decrease the cost of building and maintaining the infrastructure systems and increase the general benefit to society under constrained budgets. This dissertation adapted economic analysis theory to developed platforms to evaluate the opportunities and challenges associated with implementing new techniques for marinating or improving current infrastructure systems. The main contribution of this study is adapting and applying economic analysis theory to facilitate decision-making process for various disciplines in infrastructure development.

Adapting economic analysis theory to develop these platforms were the common is the single underlying theme in all of the publications presented in this dissertation. The steps followed for developing these platforms are presented in 8-1. The components in each computational platform were identified in the beginning of each project. These components are the major factors which have a significant impact on the output of the decision-making platform. Each component was a mathematical model which obtained through literature review or built through analyzing available data.

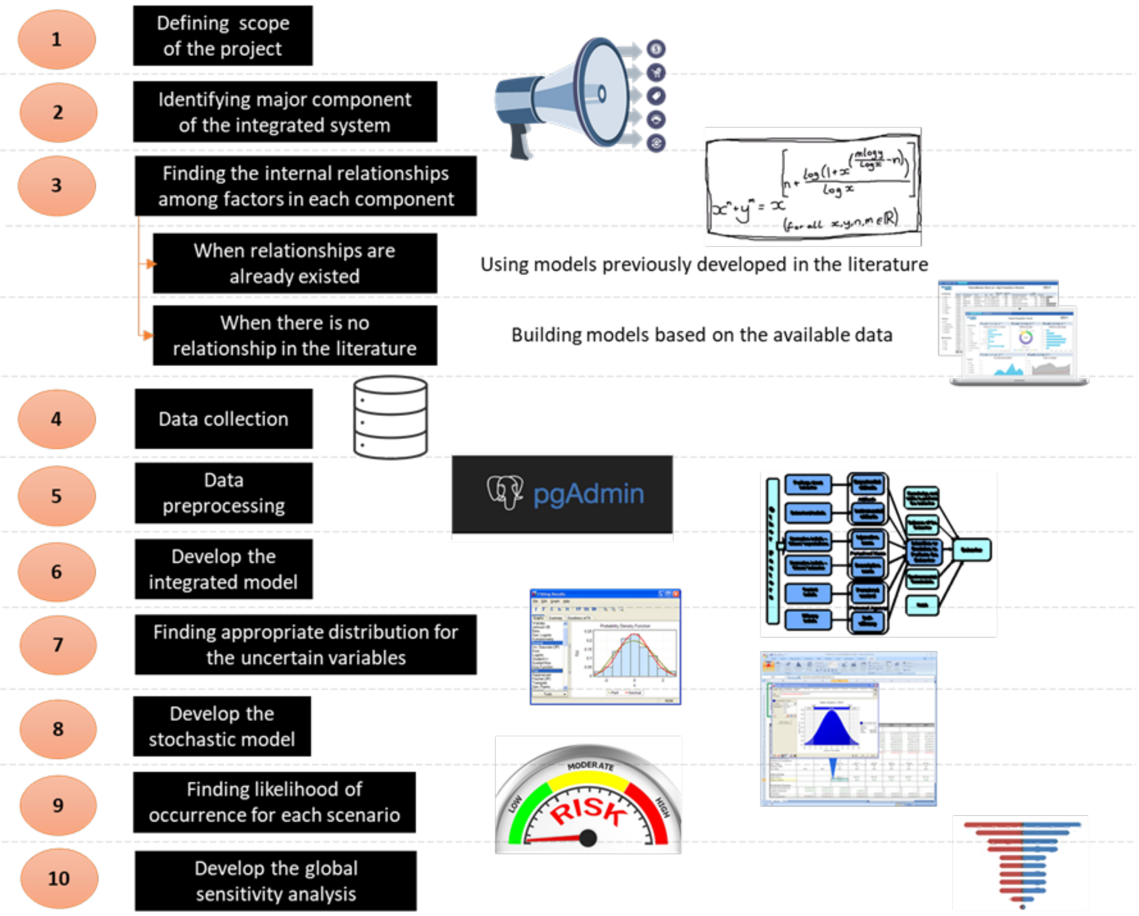

Figure 7-1 Integrated stochastic decision-making platform development

The process used in this paper could be extended to examining the economic viability of other similar heated pavement technologies (e.g. electrically conductive asphalt/PCC concrete) and also similar techniques for maintaining low volume roads (i.e. other type of seal coatings).

Heated pavement systems

The first three studies utilized heated pavement systems as a case study to develop an economic analysis platform to evaluate commercial feasibility of this emerging technology. Result of sensitive analysis showed that BCR along with construction cost largely depends on and size of the airports, in terms of aircraft operations. For example, in the ORD case, duration of delays and number of operations had significant influence on BCR. However, the impact of number of operations in the case of MKE was much lower than construction cost. This difference mainly depends on larger number of aircraft operations at ORD. Some airports may only benefit from use of ECON HPS in portions of the apron area, so it is crucial to investigate strategic installation of ECON HPS. In addition, according to the stochastic sensitivity analysis results construction cost was the most significant factor affecting benefit cost ratio (BCR). By improvements in ECON materials technology (e.g., improving the conductivity of the system) and advancements in construction practices (e.g., increasing contractor knowledge and experience) initial construction cost of ECON HPS may decrease, which has a noticable impact on BCR. Finally, under various financing circumstances (e.g. loan periods and interest rate) increase in airline ticket prices would vary from 25 cents to 65 cents.

Low volume roads

The rest of the dissertation was dedicated to two different studies on low-traffic volume roads. The first two papers on this topic evaluate feasibility of Otta seal implementation on Iowa and Minnesota low volume roads as an alternative for the conventional paved and unpaved road preservation techniques. One of the papers, Deterministic and Stochastic Life-Cycle Cost Analysis for Otta Seal Surface Treatment, uses both deterministic and stochastic LCCA approaches to evaluate the economic feasibility of using Otta seal in place of chip seal, with results leading to the conclusion that the use of Otta seal, a technology based on the use of local aggregate, would lead to reduction in transportation and material cost, thereby decreasing total construction costs. Since Otta seal technology is already being used successfully in the state of Minnesota, public agencies might be inclined to use it to reduce the maintenance cost of low-volume roads. However, the inputs can be modified, and the method can be applied to the new inputs in order to produce results that are appropriate for other localities.

The other paper in this section, Economics of Upgrading Gravel Roads to Otta Seal Surface, evaluates the feasibility of Otta seal implementation as an alternative surface treatment for low-volume roads and to evaluate the cost-effectiveness and performance of Otta seal compared to traditional bituminous seal coat surfaces in terms of maintenance of gravel roads. The key finding of this paper was determining the appropriate times for upgrading gravel road to surfaces covered with BSTs, taking traffic volume into consideration for low volume roads in Midwest. The result of this study reveals that for 15% of gravel roads, it might be possible to justify Otta seal surfacing based solely on financial analysis (not considering socio economic and environmental factors).

The methodology followed in these two papers furnish agencies with a probability that the preferred alternative will actually produce the lowest life cycle cost, so recommendations that may result from this research projects will not only be founded in fundamental LCCA theory but will also provide various public transportation agencies with an added level of confidence in predicting the financial result of pavement treatment alternatives of interest.

The other paper, and the last paper, in this dissertation focused on developing a methodology to compare the life cycle cost of various aggregate options for Iowa unpaved road resurfacing. The findings of this study suggested that IRI and dust production were proper performance measures for estimating maintenance frequency. In addition, among alternatives, Bethany Falls Limestone Class A, compared to the base case aggregate option, exhibited the best economic performance. These findings could help agencies, county engineers, and contractors in estimating the most beneficial material alternatives in terms of lower costs of hauling, material, labor, and equipment for construction and maintenance of granular roads. In addition, the methodology developed in this study provides agencies with the probability that a preferred alternative can produce the lowest life-cycle cost.

Recommendations that may result from this research project would be founded in fundamental economic analysis theory and can also provide various transportation agencies with an added level of confidence in predicting economic impact associated with granular road material alternatives of interest.