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Towards resilient infrastructure systems for winter weather events: Integrated stochastic economic evaluation of electrically conductive heated airfield pavements

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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% 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% relative likelihood that the BCR ratio of implementing ECON HPS in MSP would be greater than one.

1. Introduction

Recent studies on resilient infrastructure systems have focused on converting pavements from a passive into an active player in the urban environment. Examples include, photocatalytic pavement (Dylla & Hassan, 2012), cool pavements (Qin, 2015), and heated pavement systems (Tuan & Sherif, 2004). Many studies have shown that airports are one of the key factors in the development of the U.S. economic growth (Brown & Pitt, 2007; Hye-jin & 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 deicing 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 & Mangia, 2012; Monsalud, Ho, & Rakas, 2014; Shen, Ceylan, Gopalakrishnan, Kim, & Nahvi, 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

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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 & Mangia, 2012).

To support resiliency in communities to regularly overcome otherwise debilitating winter weather-related challenges, new alternative technologies and materials are needed (Pan, Wu, Xiao, & Liu, 2015). These techniques include electrically heated pavement systems (EHPS) (Abdualla et al., 2016; Gomis, Galao, Gomis, Zornoza, & Garcés, 2015; Sadati, Cetin, & Ceylan, 2017), hydronic heated pavement systems (HHPS) (Thurston, Culver, & Lund, 1985), super-hydrophobic coating techniques (Arabzadeh, Ceylan, Kim, Gopalakrishnan, & Sassani, 2016a, 2016b), 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, Liu, & Fei, 2014) and high materials cost, especially in the case where nanoparticles 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, Zhao, & Chen, 2008), the addition of steel fiber to a concrete mix results in drawbacks such as corrosion (Wu, Liu, & Yang, 2014), 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 4.5 m × 3.8 m 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 Fig. 1. This test setup represents the first full-scale electrically-conductive concrete ECON HPS at a U.S. airport.

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 & Scheepbouwer, 2010; Stephan & 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.

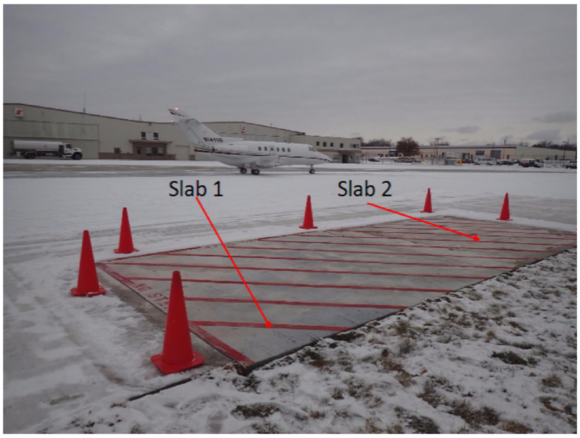

Fig. 1. Electrically conductive concrete (ECON) test slabs built at Des Moines International Airport (DSM) (photo taken December 23, 2016).

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.

2. 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 & Diekmann, 2004; Gransberg & 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 & Scheepbouwer, 2010; Pittenger, Gransberg, Zaman, & Riemer, 2012). An analyst not thoroughly acquainted with underlying engineering economic analysis theory may inadvertently choose input values that create invalid output (Gransberg & 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 & Pidwerbesky, 2007; Nahvi, 2017; Pittenger et al., 2012; Reigle & Zaniewski, 2002), was employed in this study to explore the cost effectiveness of ECON, as described in Section 2.1.

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). Fig. 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,