



USDOT Region V Regional University Transportation Center Final Report

NEXTRANS Project No. 082PY04

Internal Curing as a New Tool for Infrastructural Renewal: Reducing Repair Congestion, Increasing Service Life, and Improving Sustainability

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TECHNICAL SUMMARY

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Title

Internal Curing as a New Tool for Infrastructural Renewal: Reducing Repair Congestion, Increasing Service Life, and Improving Sustainability

Introduction

Internal curing has recently been developed as a new concrete technology that has the potential to dramatically extend the service life of concrete infrastructure elements like bridge decks. Internal curing uses prewetted lightweight aggregate in low water to cement ratio, high performance concrete to provide curing water at the opportune time to minimize restrained shrinkage cracking and increase hydration of the cement resulting in reduced chloride ingress and corrosion. Internal curing may be able to extend the service life of a concrete deck. The benefits of internally cured concrete bridge decks (either new or replacements) at a system level, in the context of traffic disruptions resulting from renewal/repair needs and varying traffic flow congestion levels across different timescales, is a relatively unexplored concept. This research seek to understand the potential benefits of internally cured concrete mixtures compared to conventional mixture in a transportation system, thereby filling a key gap in the current internal curing literature.

Findings

Internal curing generally results in a significant reduction in cracking as well as an improvement in the transport properties of concrete. These benefits are due in part to the reduced self-dessication, extended degree of hydration and the densification of the interfacial regions around the LWA. It was shown that for the service life model presented herein the IC HPC concretes cast in the state of Indiana in 2013 achieve an estimated service life improvement of 3 to 4.5 times that of the conventional bridge deck concrete specified, while a field inspection of one of these bridges indicated no visible shrinkage cracking after six months of service.

Recommendations

The research addressed in this project suggests that internally cured concrete mixtures can represent an important and viable option for a transportation system to replace conventional concrete mixtures. Further, this research serves as a building block for exploring a new generation of analytical frameworks for application of internally cured concrete mixture.

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CHAPTER 1. SERVICE LIFE ESTIMATION OF COMMERCIALY PRODUCED INTERNALLY CURED, HIGH PERFORMANCE CONCRETE

1.1 Introduction

Internal curing is a process in which internal reservoirs containing water (pore solution) are provided in the concrete at the time of casting, which later act to refill the void space created due to chemical shrinkage during the early stages of hydration in cementitious systems (Bentz and Snyder, 1999). As the pores within the concrete self-desiccate, water is pulled from the internal reservoirs by the development of capillary pressure and migrates to refill the surrounding pores of the matrix as they empty. Proposed vessels for achieving internal curing include super absorbent polymers (SAPs) (Jensen and Hansen, 2001), wood fibres (Mohr, et al., 2005), and fine lightweight aggregate (LWA) (Philleo, 1991). To date, much research exists on the theory and the application of internal curing in laboratory studies and has been summarized in recent state of the art reports (Kovler, et al., 2007; ACI, 2010; Bentz and Weiss, 2010; Mechtcherine and Reinhardt, 2012). This paper will focus on reporting on the field implementation of internal curing through the use of a prewetted LWA as a partial replacement of the fine aggregate and the estimated lifecycle of these materials.

While the body of research regarding internal curing is vast, the documentation of field implementation of internally cured concrete and the performance of these materials is still needed. Recent work has highlighted the construction of internally cured bridge decks made by replacing a portion of the normal fine aggregate with LWA in the USA in Indiana (di Bella, et al., 2012), New York (di Bella, 2012), and Utah (Guthrie and Yaede, 2013). Although it has been successfully used and is becoming more widely specified, apprehension still exists toward the widespread adoption of

internal curing. This in part has come from the perceived challenges of performance based specifications and the necessary quality control measures that concrete producers must undertake to achieve the performance criterion. A recent publication has reviewed the field application of internal curing and highlighted some key aspects of mixture design and quality control measures for the production of internally cured concrete mixtures (Barrett, et al., 2014). In addition, a new quality control method which is based on the use of centrifugal force to remove surface moisture of LWA has been developed and implemented in the study presented herein to rapidly and accurately determine the moisture state of LWA in field applications (Miller, et al., 2014).

In 2013, the Indiana Department of Transportation (INDOT) commissioned the construction of four bridge decks to be made with a new class of internally cured, higher performance concrete (IC HPC). In an effort to improve upon the standard bridge deck concrete which achieves an estimated service life of approximately 18 years (Weiss, et al., 2014), a ternary blended cementitious system made at moderate water-to-cementitious materials ratios (W/CM), of less than 0.43. It has been shown that materials made at lower W/CM utilizing large amounts of supplementary cementitious materials can have an increased susceptibility to cracking (Weiss, 1999; Bentur, 2003). To address this, internal curing was implemented.

The IC HPC bridge decks that were cast were made by four separate producers, located in four different regions of Indiana (INDOT districts). The projects were supervised by four different district engineering units. The bridges had varying span lengths (maximum span lengths ranged from 8.5 m to 26 m) and varying structural configurations (single span composite with steel girders, three span continuous composite with steel girders, and two span continuous composite with prestressed concrete beams with an integrally cast pier).

1.2 Objectives

This study presents an experimental investigation of the four internally cured bridge deck concretes that were cast in the state of Indiana in 2013. In addition, these same mixtures were reproduced without internal curing at the local production facilities using the same approach used for the IC HPC (henceforth referred to as simply higher

performance concrete (HPC)). The service life was then estimated for these 8 bridge deck concretes using a fundamental approach which accounts for the measured permeability, diffusion, and mixture proportions of each material. The service life of each of these mixtures will then be compared to the service life of the traditional bridge deck concrete mixture in Indiana. Finally, one of the IC HPC bridge decks was inspected after approximately 6 months of service for shrinkage cracking.

1.3 Experiment investigation

The specimens obtained in this study were produced on the same day that each bridge deck was cast using the same mixture proportions, batching and mixing system, and aggregate moisture adjustments as was used for the bridge deck. Upon completion of the deck pour, two separate concrete trucks were ordered at each producer's facility, containing 2.3 m³ (three cubic yards) of concrete each. The first truck contained the IC HPC as batched that morning while the second truck contained the equivalent HPC, where the LWA in the mixture was replaced with normal weight fine aggregate.

1.3.1 Materials

The cementitious materials used in the study include Type I ordinary portland cement, Class C fly ash or ground granulated blast furnace slag (GGBFS), and densified silica fume. The aggregate consisted of a normal weight natural fine aggregate and a normal weight limestone conforming to INDOT gradation 9 (INDOT, 2014). To achieve internal curing, an expanded shale lightweight fine aggregate was used to replace a portion of the normal fine aggregate. The LWA stockpiles were required to be soaked with water using an approved sprinkler system for a minimum of 48 hours, followed by a draining period of 12 to 15 hours immediately prior to production. The moisture state of the LWA was determined using the centrifuge method where, at the time of batching, the measured absorption ranged from 18.7 to 20.2% for all mixtures. The measured surface moisture contents of the LWA for all mixtures ranged between 6.6 to 9.9%.

1.3.2 Mixture Proportions

The as-batched mixture proportions of the concretes used in this study can be seen in Table 1. The naming convention of each mixture is denoted by the concrete mixture type (IC HPC or HPC) and a numeral indicating the base mixture for each bridge deck in no particular order. Concrete mixtures IC HPC 1 and HPC 1 were made using the same mixture proportions with the only difference being the replacement of fine aggregate with LWA for the purposes of internal curing. The design mixture proportions were specified to have a W/CM between 0.36 and 0.43, contain 20 to 25% replacement of cement by fly ash (by mass) or alternatively 15 to 20% of GGBFS (by mass), and a 3 to 7% replacement of cement by silica fume. Additionally, the mixtures were specified to have a paste content below 25%, contain 6.5% of entrained air by volume, and achieve a slump of 63.5 mm to 139.7 mm (INDOT, 2014). Air entrainer, high range water reducing agents (HRWRA), mid-range water reducing agent (MRWRA), and retardant admixtures were added at the discretion of each producer in order to meet these specifications. In mixtures which were internally cured, a volume of lightweight aggregate was used to replace normal fine aggregate at a rate such that the LWA supplied approximately 7.2 kg of water / kg of cementitious materials, following the approach set forth by Bentz and Snyder.

1.3.3 Methods

A series of 101.6 mm diameter by 203.2 mm tall cylinders were cast in the field at four separate concrete producers' facilities to obtain samples for testing. After approximately one week of curing in the field, the cylinders were transported to the laboratory where the sealed samples were placed in a wet curing environmental chamber (approximately 100% relative humidity (RH)) conditioned to 23 ± 2 °C to prevent unwanted effects of external drying.

The permeability associated with the loss of water vapour of each mixture was determined through the use of drying tests on cylindrical samples. At an age of 91 days, a set of six specimens were obtained by cutting the field cast cylinders to 101.6 mm diameter by 10 mm tall and 50 mm tall (three samples of each height). The samples were then submerged in water until they reached a mass equilibrium, considered in this

case to be the “saturated” condition. The “saturated” surface dry weight was then taken (as well as the buoyant weight) then the samples were introduced to a drying environment of 50% RH at 23 ± 2 °C. The mass change of the samples was monitored for a minimum of 6 months for each mixture. Upon completion of the drying tests, the samples were oven dried in order to obtain the porosity (ASTM, 2006).

Table 1 Concrete mixture proportions as batched [kg/m³]. Admixtures are provided in [mL/kg of cementitious materials].

	IC HPC 1	HPC 1	IC HPC 2	HPC 2	IC HPC 3	HPC 3	IC HPC 4	HPC 4
W/CM	0.405	0.428	0.396	0.403	0.447	0.422	0.465	0.398
Cement	234	236	263	263	256	256	260	272
Fly Ash	74	74	-	-	67	67	-	-
GGBFS	-	-	59	58	-	-	71	74
Silica Fume	15	15	15	15	10	10	15	15
Coarse Aggregate	1083	1088	1069	1069	1027	1023	1084	1067
Fine Aggregate	442	725	463	792	486	794	505	821
Lightweight Aggregate	195	-	205	-	249	-	301	-
Air Entrainment	35	35	12	12	18	19	23	22
HRWRA	272	270	111	112	160	206	304	289
MRWRA	-	-	-	-	33	39	73	71
Measured Air Content [%]	6.5	7.1	5.1	5.2	1.8*	5.9	8.1	7.1
Slump [mm]	90	150	200	180	50	50	230	230
Paste Content [%]	24.0	25.0	24.4	24.6	26.0*	25.2*	24.5	25.3*

*Indicates measures not conforming to limits set within INDOT specifications for IC HPC [20].

The diffusion coefficients for ionic species were measured using the STADIUM® Lab simulation technique and a migration cell. The test method is a modified version of ASTM C1202 (2012d), where the intensity of electrical current passed through a 101.6 mm diameter by 50 mm thick cylindrical specimen is monitored over a 14 day period (S.T.Inc, 2013). The samples used for this test were cut from the set of field cast samples. After the samples were cut, the sides of the samples were

sealed with an epoxy after which they were vacuum saturated at a pressure of 6 ± 3 Torr with 0.3 M NaOH solution approximately 18 hours prior to the start of testing. Once saturated, the samples were mounted between a cell filled with 0.3 M NaOH solution (downstream) and a cell filled with 0.5 M NaCl + 0.3 M NaOH solution (upstream). A constant DC potential of 20V was maintained across the specimen for 14 days while the voltage, current, and temperature were measured and recorded at 5 minute intervals [10]. The results from the migration cell and the volume of permeable voids were then used in STADIUM® Lab software to evaluate the ionic diffusion coefficients and the tortuosity of the samples (Samson, 2003).

The results from the permeability tests and ionic diffusion tests, as well as mixture proportions and material compositions were then used in the STADIUM® simulation package to estimate the service life of the bridge deck materials; this method follows the outlined procedure in the STADIUM® technical guide (S.T.Inc, 2010). Using this approach, the service life is estimated using the extended Nernst-Planck equation coupled with Richard's equation to model the ionic diffusion in unsaturated cementitious materials. Specifically, this approach calculates the transport of the ionic species through the concrete due to surface exposure to deicing salts (in this case, NaCl) while taking in to account the effects of ionic diffusion, electrical coupling, chemical activity, temperature dependence, and advection. The physical binding of chlorides is accounted for from step-wise calculations of internal chemical equilibrium between the pore fluid and the solid phase using the mixture proportions and chemical compositions of the binding materials.

To be consistent for the simulations, the exposure condition for each bridge deck mixture was chosen to be representative of Indianapolis, Indiana, where the exposure temperature cycled about an average temperature of 11 °C with an amplitude of 13 °C over the course of each year. The average exposure RH for the materials was set to be 70.5% while exposure to sodium chloride was set for a period of 45 days with a peak exposure concentration of 400 mmol/L (approximately 2.8% NaCl by mass). The chloride content was calculated at the level of the top layer of reinforcing steel, located

at a standard depth of 50.8 mm. The simulations were carried out for 120 years, with a time step of 24 hours.

1.4 Results and discussion

The results from the permeability test can be seen in Table 2. In general, it can be noticed that the measured volume of permeable voids is greater in internally cured mixtures, however this is likely an artifact of the testing method in which the porous lightweight aggregates are exposed when the samples are cut. Further evidence of this phenomenon can be seen by estimating the desorption isotherm as calculated by Equation 1, where the water content, w , is estimated as a function of relative humidity, H . The parameters β and δ are fitted from the drying test described previously and ϕ is the measured volume of permeable voids. Figure 1 shows a comparison of the estimated isotherms for IC HPC 4 and HPC 4, where it can be noticed that in general, the difference in volume of pores exists largely at the highest relative humidities. Using the Kelvin-Laplace equation to estimate the size of the voids that would be emptying at these high RH, it becomes clear that these are the largest pores in the system, which is consistent with drying occurring in the larger pores of the exposed lightweight aggregates.

Inspection of the permeability coefficients of each mixture yields no general trend between HPC and IC HPC, with the internally cured mixtures having lower permeability in the second and third series while it is higher in the first and fourth. Additionally, there seems to be no correlation between the magnitudes of the permeability in relation to W/CM or mixture proportions. It is perhaps worth noting that the volume of entrained air was lower for IC HPC 2 and 3 in comparison to IC HPC 1 and 4, which may have resulted in the lower permeability for these mixtures in reference to their non-internally cured counterparts, as water occupying this space would be lost easier resulting in higher permeabilities.

Table 2 Results from moisture desorption testing for water vapour permeability

	IC HPC 1	HPC 1	IC HPC 2	HPC 2	IC HPC 3	HPC 3	IC HPC 4	HPC 4
Volume of permeable voids, ϕ [%]	13.0	11.7	12.8	11.9	15.0	12.5	13.8	11.7
Permeability [$e-22 \text{ m}^2$]	18.0	14.8	19.8	34.7	12.0	18.2	10.1	3.31
β Parameter	-145.0	-156.9	-163.2	-176.6	-89.2	-111.8	-100.1	-89.40
δ Parameter	0.10	0.11	0.10	0.10	0.11	0.11	0.11	0.10

Note: Average coefficient of variation for permeability measurements is 20.6% [25].

$$w = \frac{\phi}{\beta\phi(H^\delta - 1) + 1} \quad (1)$$

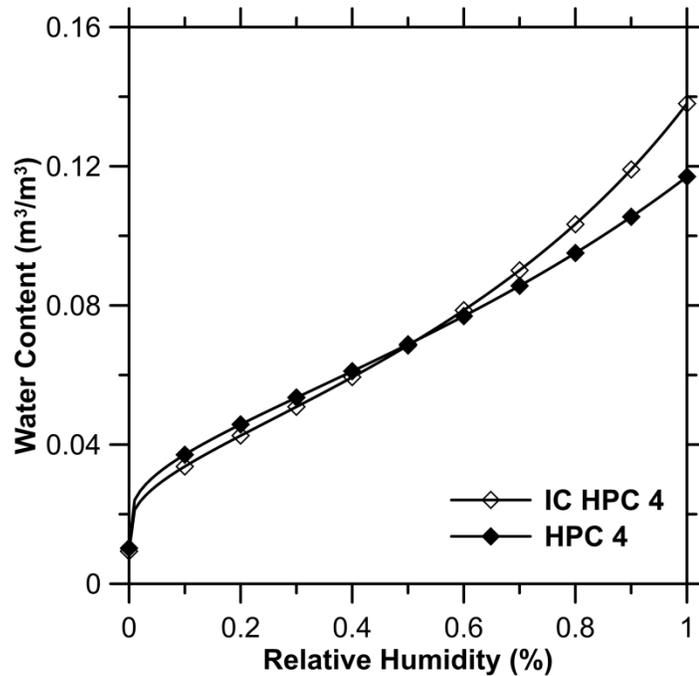


Figure 1 Estimated desorption isotherm for IC HPC 4 and HPC 4

The results of the migration cell testing can be seen in Table 3. It should first be noted that the method presented here differs from similar migration methods in that the diffusion coefficients are calculated over the pore volume and not the bulk of the sample. In addition, the calculations assume a linear relationship between diffusion coefficients and tortuosity, hence the relative differences hold for both measures. It can be seen that the tortuosity of IC HPC 1, 2, and 3 are significantly lower than their non-internally

cured counter parts, with reductions of 28%, 51%, and 56% respectively. This reduction in tortuosity (and chloride diffusion) can be attributed to the extended degree of hydration due to the additional water from internal curing and the densification of the matrix adjacent to the lightweight aggregates and is consistent with previous findings [26, 27]. For IC HPC 4, a 12% increase in tortuosity is observed and is likely attributable to the increase in W/CM in relation to HPC 4. In comparison to a recent study performed on the traditional bridge deck mixtures (i.e., Class C concrete), the magnitude of the chloride diffusion coefficients of the mixtures presented here are 1.75 to 8 times lower (with the Class C concrete having a chloride diffusion coefficient reported as $7.67E-11$ m²/s at 91 days).

Table 3 Calculated chloride diffusion coefficients and associated tortuosity from migration cell testing.

	IC HPC 1	HPC 1	IC HPC 2	HPC 2	IC HPC 3	HPC 3	IC HPC 4	HPC 4
Cl⁻ Diffusion Coefficient [e-11 m²/s]	0.96	1.32	2.38	4.83	1.43	3.32	1.32	1.18
Tortuosity	0.0047	0.0065	0.0117	0.0238	0.0071	0.0163	0.0065	0.0058

Note: Average coefficient of variation for ionic diffusion coefficients is 11.1% [25].

The results of the service life simulations for the eight bridge deck materials can be seen in Figure 2, where the total chloride content of each mixture at the depth of the reinforcing bar is plotted as a function of time. The dashed line on the plot indicates a critical threshold for the initiation of the corrosion of the reinforcing steel, set at 0.5% as suggested by STADIUM® and based upon research conducted by the Federal Highway Administration (McDonald, et al., 1998). The estimated service life of IC HPC 2 and 3 is approximately 60 years, while IC HPC 4 achieves a service life of 73 years and IC HPC 1 reaches 92 years before the initiation of corrosion. The HPC 2 and 3 mixtures achieve lower service lives of 30 to 35 years, which may be associated with the higher permeability and greater connectivity of the pore structure (i.e., higher tortuosity) of the HPC 3 mixture. HPC 1 and 4 are both estimated to achieve longer service lives than their internally cured counterparts, however it should be acknowledged that this model

does not account for the potential for cracking, which would expedite deterioration. Perhaps the most important takeaway from this service life estimation however is the relative comparison to the standard bridge deck mixture used in Indiana which has an estimated service life (using the same methodologies presented here) of 18 years. The bridge deck materials in this study achieve a corrosion based lifecycle of nearly 2 to 5 times longer than the standard Class C mixture, with the internally cured mixtures showing 3 to 4.5 times longer lifecycles while also addressing the potential for cracking through internal curing. It should be noted here that variability in these service life predictions is expected as the associated measurement techniques for determining the input parameters contains a documented amount of variation, however the extent to which this effects the service life predictions has not yet been determined and is an ongoing subject of investigation.

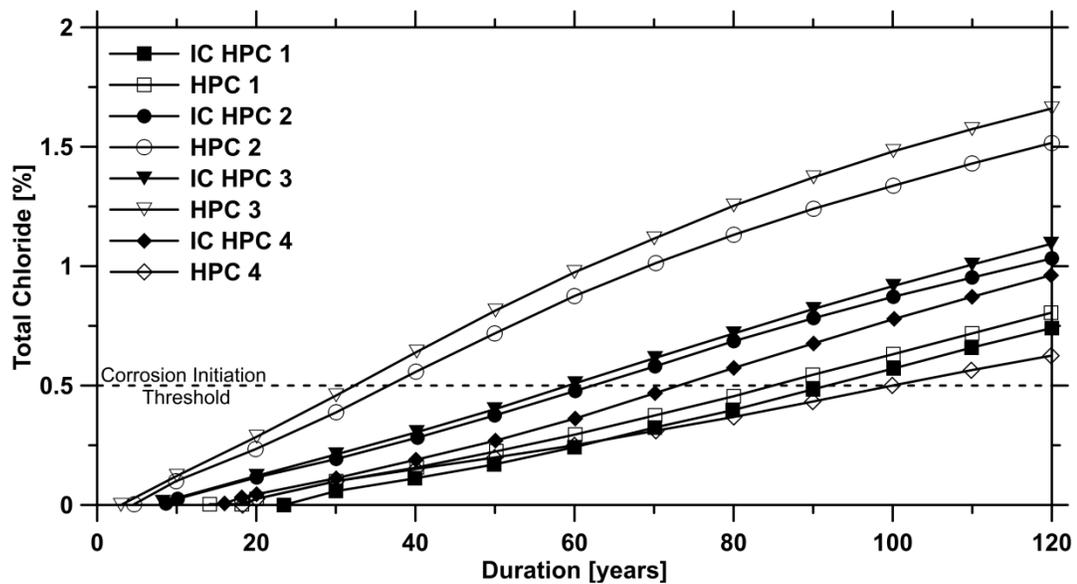


Figure 2 Total chloride content versus time for each mixture. (Corrosion initiation threshold for reinforcing steel indicated by dashed line at 0.5%)

After approximately six months of service, a visual inspection for cracking was performed on the bridge deck which consisted of the material referred to herein as IC HPC 4. Upon inspection, it was found that two cracks were present in the bridge deck, located directly above the integrally placed pier (at either edge of the pier), while no other signs of cracking was identified. Due to the structural configuration of this bridge

(two continuous spans cast compositely with prestressed beams) it is likely that these cracks are due to the restraint provided by the integral pier and the negative moment induced in the bridge deck above this pier from traffic loading. Evidence of transverse cracking that is consistent with shrinkage cracking in higher performance concretes used in bridge decks was not found. Further observations of this bridge deck and the others involved in this study will be made, however it is believed that the use of internal curing has effectively reduced the potential for shrinkage cracking due to volumetric changes in the concrete material used to construct the decks. These findings are similar to field observations made in which an internally cured Class C concrete bridge deck showed no cracking during inspection after 20 months of service, while a second bridge made during the same week which consisted of standard Class C concrete contained two transverse cracks.

CHAPTER 2. EVALUATING THE IMPACT OF INTERNALLY CURED CONCRETE ON TRAFFIC CONGESTION

2.1 *Introduction*

As a new concrete technology, the internally cured concrete has its unique characteristics that dramatically extend the service life of concrete infrastructure elements and thus reduce the costs associate with renewal and repair expenses as well as the traffic disruption impacts. This chapter focuses on evaluating the costs due to the traffic congestion induced by repairing, replacing or rehabilitating bridge decks in a transportation network. The long-term benefit of the internally cured concrete, in terms of the impacts on traffic flow due to the construction disruption, is quantified through the evaluation

Over the past years, great progress has been made in the field of performance masurement for work zones, alternative contracting, and construction techniques, all of which are designed to minimize, manage, and mitigate the disruption impact to traffic arising from renewal programs. During the construction periode for repairing or replacing the bridge decks, the travel behavioral and route choices change due to the capacity reduction of road segements. These distruptions would increase the travel cost for drivers in the system due to the increasing travel time. In order to capture the travel time increase due to construction, the problem is usually formulated in the context of traffic assignment problem (TAP). And the total system travel time difference between the pre-construction period and under construction period represents the distruption to the traffic caused by the construction. To quantify the benefits of internally cured concrete over traditional concrete mixture to the users, the value of travel time (VOT) is

used to translate the travel time increased into the user monetary cost in the benefit-cost analyses of internally cured concrete.

In application, however, the traditional evaluation approaches of the costs of concrete infrastructure are mostly applied at the individual project, and the resultant traffic impact is not analyzed as an integrated entity at the program level in the planning process. In this project, we develop a model and a solution algorithm that efficiently assist program practitioners in evaluating the performance of roadway construction projects in using internally cured concrete.

2.2 *Literature review*

Over the last few decades, extensive research has been done to improve the bridge decks repairing or replacing process and all of them are designed to balance the two main objectives of the repairing or replacing process. One is to minimize the total life-cycle cost of concrete bridges decks, and the other is to mitigate the user and environmental impacts.

The total life-cycle cost of concrete bridges decks often has three main components, including agency costs, user costs, and environmental costs (Kendall et al. 2008). Agency costs represent the expenditures incurred by the facility owner or operator in charge of the bridge deck construction/replacement, inspections and maintenance, repair and rehabilitation throughout the life-cycle of that bridge deck, minus residual value of that bridge deck at the end of the life-cycle. These costs are usually been converted to present value in the total life-cycle cost analysis (Cusson et al., 2010; Sinha and Labi, 2007). However, majority of the studies either consider only the agency costs when they compare different construction scheduling or materials, or assume a fixed life-cycle without considering the impact of environment or traffic flow volume. Kendall et al. (2008) found that the total agency costs only account for 3% of the total life-cycle costs of concrete bridges decks, while the largest portion of total life-cycle costs of concrete bridges decks (over 90%) comes from the user costs. In practice, social discount rate is often used for agency costs calculation, as the potential benefits of public projects may not be reflected in today's market (Campbell and Brown, 2003).

User costs are often considered as the monetized value of vehicle operating costs, travel-time costs, and safety costs. During the construction or maintenance period, the traffic disruption caused by the capacity reduction of the concrete bridge deck lead to increase in total system travel time and increased traffic crashes related to construction work zones. The increase of total travel time can lead to operating cost increase (e.g. increased gasoline consumption due to longer travel time) and travel-time costs. To quantify the user impact due to travel time increase during construction period, the problem is usually formulated in the context of traffic assignment problem (TAP), by comparing the system total travel time difference between the pre-construction period and under construction period. One basic assumption about traffic assignment model is user equilibrium flow pattern, meaning “the journey times in all routes actually used are equal and less than those which would be experienced by a single vehicle on any unused route” (Wardrop, 1952). However, these studies often limited to the user cost within a relatively short-term construction planning period and these costs are not factored in the life-cycle cost. The potential long-term demand changes are often not captured in this study. For the safety costs during the construction or maintenance period, extensive studies (e.g., Ha and Nemeth, 1995) have been done in this domain and they show that the cause of crashes related to traffic control plan used, implementation of the traffic control plan, and individual driver’s characteristics, etc. And the unit crash costs are often valued based on Police-Reported Injury Severity System (KABCO) coding scheme (National Safety Council, 2014).

The environmental costs of concrete bridges decks in the total life-cycle costs often include air pollution costs, noise costs, water pollution and runoff costs, and community disruption. The air pollution costs are often reflected on the total emission increase caused by the increased travel time due to traffic disruption during the construction or maintenance periods (Kendall et al., 2008). However, noise costs, water pollution and runoff costs are often hard to quantify and the costs varies significantly case-by-case (Sinha and Labi, 2007).

A large body of work on the simulation method and Life-Cycle Cost Model (LCCA) are often applied in the domain of various civil engineering structure sand

facilities has been conducted in the last two decades, and numerous studies have applied on evaluating different replacement/construction/maintenance options of bridge decks (Eamon et al., 2012). These studies utilized the agency, user and environmental costs with probabilistic analysis and Monte Carlo Simulation (MSC) was used to generate simulated activity timing. The major different of these studies are the methods used to calculate the individual costs and the inclusion of some new components of the individual costs. However, most of these studies only consider the performance of individual bridge decks without considering the transportation system.

Apart from considering alternative construction scheduling and planning, significant efforts have been spend on developing new material mixture to reduce the total life-cycle cost and the impact on environment and users. Internal curing has recently been developed as a new concrete technology that has the potential to dramatically extend the service life of the concrete infrastructure elements like bridge decks. Internal curing describes a process that internal reservoirs containing water can act to refill the void space created due to chemical shrinkage during the early stages of hydration in cementitious systems, if been provided in the concrete at the time of casting (Bentz and Snyder, 1999). This process has been applied to bridge decks construction in three different states (Indiana, New York and Utah) of the U.S. using fine lightweight aggregate as vessel to achieve internal curing (Philleo 1991). A recent study (Barrett et al., 2011) shows that the simulated service life of commercially produced internally cured, high performance concretes have the potential of triple the estimated 25 years of service life for a conventional bridge deck concrete. Extensive studies have been done in the field of internally cured bridges decks to identify the parameters needed for service life prediction (Philleo, 1991), internal curing mixtures used in the field (Bentz and Snyder, 1999), and develop total life cycle cost models to quantify the benefit of internally cured concrete mixtures over conventional concretes (Cusson et al., 2010). However, a key issue is that very little systematic study has been conducted to examine the benefits of internally cured concrete bridge decks at a system level to quantify its potential impacts in the context of traffic disruptions resulting from renewal/repair needs and varying traffic flow congestion levels across different time scales.

To comprehensively evaluate the total life-cycle cost of internally cured concrete bridge decks, in the present study, the impact on user costs is formulated as a traffic assignment problem (TAP) under the traffic disruption scenario due to the bridge decks repair/replacement. In planning community, the TAP is used to evaluate corridor and network management performance for transportation improvements, which requires analyzing the entirety of infrastructure needs within that corridor and/or network. Such analyses integrate the networkwide impacts, including travel delay due to disruption to the traveling public, interference to commerce, and effect on the local community. Evaluations of roadway construction projects during the planning process prefer to recognize the redistribution of traffic due to closures or restrictions on the right-of-way imposed by work zone activities.

The traffic assignment model that is widely adopted in evaluating the performance of roadway construction projects is established on the assumption of user equilibrium (UE) flow pattern. User equilibrium, also known as Wardrop's first principle, states that: "The journey times in all routes actually used are equal and less than those which would be experienced by a single vehicle on any unused route" (Wardrop 1952). The user equilibrium TAP has led to its widespread applications since Beckman formulated it as a convex optimization problem (Beckman et al., 1956). The basic model remains widely used in planning, and finding fast algorithms for solving the TAP is of interest to both researchers and practitioners world-wide. The estimation of user equilibrium can also be achieved through solving complementarity, variational inequality, or fixed point problems.

The Frank-Wolfe (FW) algorithm (Frank and Wolfe, 1956; LeBlanc et al., 1975) appeared the first widely applied algorithm that has promoted the TAP in practice over the past few decades. The downside of FW, however, lies in its long tailing effect during convergence, making it difficult to reach the nominal objective function value, due to ineffective search directions when the solution is near the optimum. A steady stream of research has been found attempting to improve the convergence of the FW algorithm, by a means to identify either a better search direction (LeBlanc et al., 1985) or an improved step size (Powell and Sheffi, 1982).

It has long been recognized that the TAP is equivalent to a min-cost multi-commodity flow problem on an uncapacitated network with a convex, continuous derivative objective function, where each commodity is characterized as originating from a single origin. Hence, a variety of algorithms (Nguyen 1974; Petersen 1975) have been proposed to decompose the master problem by solving the single commodity subproblems repeatedly until all of the commodities are optimized simultaneously. Such algorithms nowadays are known as “origin-based”.

Origin-based algorithms for the TAP have recently been promoted substantially, due to a family of bush-based algorithms. Representative algorithms scoped in this family by our notation include Origin-Based Algorithm (OBA) (Bar-Gera 2002), Algorithm B (Dial 2006), and their variants (e.g., Gentile 2012; Nie 2012; Nie 2010). Several common features and key building blocks are shared by all algorithms featured in this family – (1) the algorithm recognizes the fact that the UE flow associated with a single origin never forms a directed cycle; (2) the algorithm solves the subproblems of single-origin commodity flow iteratively; (3) for each origin, the algorithm maintains an acyclic sub-network (meaning no directed cycles), and restricts traffic assignment on the acyclic sub-network only; and (4) the algorithm changes the acyclic sub-network iteratively until the acyclic sub-network possesses all arcs that carry the positive-value flow in a UE solution. An acyclic sub-network maintained in the intermediate computations is called a bush, due to Dial (2006). The acyclicity of a bush is a key building block in the design of a fast algorithm in this family, which allows the fastest possible shortest-path-tree and, perhaps more importantly, the longest-path-tree computations. The main differences in the above algorithms lie in the variations of solving the equilibrium flow restricted on a bush, which is also called the restricted master problem. Recently, Bar-Gera (2010) proposed another related algorithm called Traffic Assignment by Paired Alternative Segments (TAPAS). TAPAS focuses on a more specific structure called a Paired Alternative Segments (PAS). Sending flows around a PAS is equivalent to shifting flows from the high cost segment to the low cost segment, thus exhibits certain similarity to Algorithm B. Overall, the family of bush-based algorithms has been found to be more efficient than its link-based or path-based

counterparts (Florian et al. 2009; Jayakrishnan et al. 1994) in terms of producing highly precise UE solutions with modest computational time and memory usage. For a survey of the family of bush-based algorithms, see (Nie 2010).

To estimate the traffic flow redistribution under roadway construction, this study employs an algorithm that is characterized by the “origin-based” feature but out of the “bush” family; namely, we solve the origin-based flow without using a bush. The proposed algorithm is featured by a convex simplex algorithm, which operates simplex tableaus on the tree to repeatedly solve the single-origin TAP with a convex cost function subject to a set of linear network constraints. The main method of the algorithm is cycle cancellation, which augments flows around a negative cost cycle to zero the cycle’s cost. This idea is similar to the generalized cycle briefly mentioned in TAPAS (Bar-Gera 2010). However, TAPAS focuses on a more specialized cycle, called PAS, which is characterized by either having all segments be backward arcs, or having one segment composed of forward arcs only and the other composed of backward arcs only. In contrast to PAS, we work on a generalized cycle without restriction of the cycle’s topology. Our algorithm maintains a spanning tree, which is the same structure commonly seen in a network simplex algorithm, for the purpose of detecting cycles efficiently. We show that through appropriate implementation of the data structure and algorithmic design, the proposed algorithm is capable of producing highly precise solutions and achieving fast convergence.

As TAP plays the critical role in evaluating the impact of internally cured concrete, the following sections will focus on the analytical formulation and solution algorithms for the TAP used in the life cycle analysis of internally cured concrete. A numerical example will be provided to compare the total life-cycle costs of conventional concrete mixture and internally cured concrete mixture on a metropolitan transportation network.

2.3 *Notation*

This section provides the notation and the concept of cycle that will be used to establish the analytical model and solution algorithm for redistributing traffic flow under roadway construction. A transportation network $G = (N, A)$ consists of a set of nodes N

and a set of directed arcs A (also called links). Suppose that the network is strongly connected, i.e., between any two nodes there exists at least one route. Flow assigned on arc $(i, j) \in A$ is denoted by x_{ij} . Each arc $(i, j) \in A$ is associated with a non-negative flow-dependent cost (or travel time) $c_{ij}(x_{ij})$, or simply c_{ij} sometimes for notational convenience. N consists of a set of origins, denoted by \mathcal{P} , a set of destinations, denoted by \mathcal{Q} , and a set of intermediate nodes. A set of origin-destination (O-D) pairs is denoted by a vector $V := \{(p, q): p \in \mathcal{P}, q \in \mathcal{Q}\}$. In the origin-based TAP, a set of destinations associated with an origin $p \in \mathcal{P}$ is denoted by $\mathcal{Q}(p)$. Demand from each origin $p \in \mathcal{P}$ to its destination $q \in \mathcal{Q}(p)$ is denoted by d_{pq} . Denote the total demand of origin p by D_p , where $D_p = \sum_{q \in \mathcal{Q}(p)} d_{pq}$. Denote by $I(i)$ a set of inbound arcs ending at node i ; denote by $O(i)$ a set of outbound arcs outgoing from node i . Denote by \mathcal{R}_{pq} a set of simple routes¹ between an O-D pair $(p, q) \in V$; by f_r^{pq} the flow on route $r \in \mathcal{R}_{pq}$; by c_r^{pq} the route travel time on $r \in \mathcal{R}_{pq}$; and by π_{pq} the travel time on the shortest route from p to q .

A walk visits a list of nodes i_1, \dots, i_n such that for each $k = 1, \dots, n - 1$ there is $(i_k, i_{k+1}) \in A$ or $(i_{k+1}, i_k) \in A$. The walk is a directed walk if $(i_k, i_{k+1}) \in A$ for each $k = 1, \dots, n - 1$. A cycle, denoted by W , is a walk where $i_1 = i_n$, and also, $i_k \neq i_{k+1}$ for $k = 1, \dots, n - 1$ and $n > 2$. A directed cycle is a directed walk with the same conditions of a cycle. Note that a cycle discussed in the remainder of the paper refers to a non-directed cycle unless otherwise noted. A graph is acyclic if it does not contain any cycles. A tree is a connected acyclic graph. A subgraph is a graph (N', A') such that $N' \subseteq N$ and $A' \subseteq A$. A spanning tree, denoted by \mathcal{T} , is a subgraph with $N' = N$ that is also a tree. An in-tree-arc is downward wrt \mathcal{T} if it is directed away from the root, is upward if directed toward the root.

A cycle W has an orientation (also called direction), which is either clockwise or counter clockwise. A cycle that consists of the same arcs in W but has the opposite orientation of W is called a reversal cycle of W , denoted by $-W$. A set of arcs $\{(i, j) \in W\}$ that have the same direction as the cycle is called a set of forward arcs, denoted by $F(W)$; a set of arcs that have the reverse direction of the cycle's direction is called a set

¹ A simple route is a route that contains no cycle.

if backward arcs, denoted by $B(W)$. Figure 3 illustrates the examples of forward and backward arcs in a cycle that has a clockwise orientation, where arcs $(1,3)$, $(3,5)$, $(5,6)$ and $(4,2)$ are backward, and arcs $(1,2)$, $(4,6)$ are forward. A forward arc in W becomes backward in $-W$, and a backward arc in W becomes forward in $-W$.

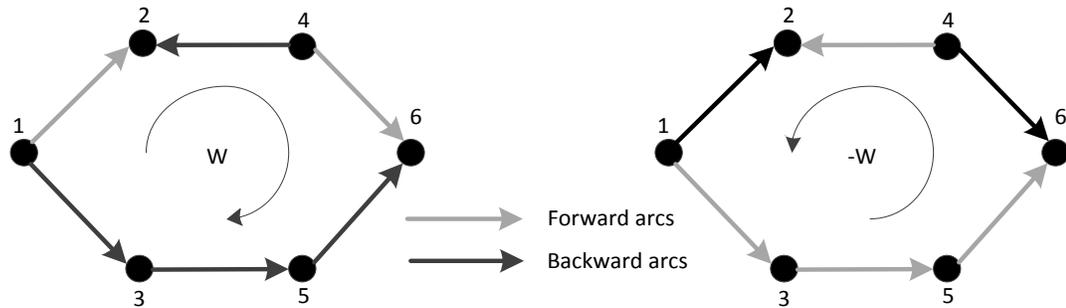


Figure 3 Forward and backward arcs in a cycle

Given a cycle W , the flow vector $\mathbf{x}^W = \{x_{ij} : (i, j) \in W\}$ with components

$$x_{ij} = \begin{cases} 1 & \text{if } (i, j) \in F(W) \\ -1 & \text{if } (i, j) \in B(W) \\ 0 & \text{otherwise} \end{cases}$$

is called a simple circulation associated with W . Let $\mathbf{x} = (x_{ij})_{(i,j) \in A}$ be a flow vector, and let σ be a non-negative scalar; we say that the flow vector $\mathbf{x} + \sigma\mathbf{x}^W$ is obtained from \mathbf{x} by sending σ units of flow around cycle W . This operation increases the flow on the forward arcs in the orientation of W by σ units and decreases the flow on the backward arcs by σ units. Figure 4 demonstrates the method of augmenting flows around a cycle, where the cycle's direction is clockwise.

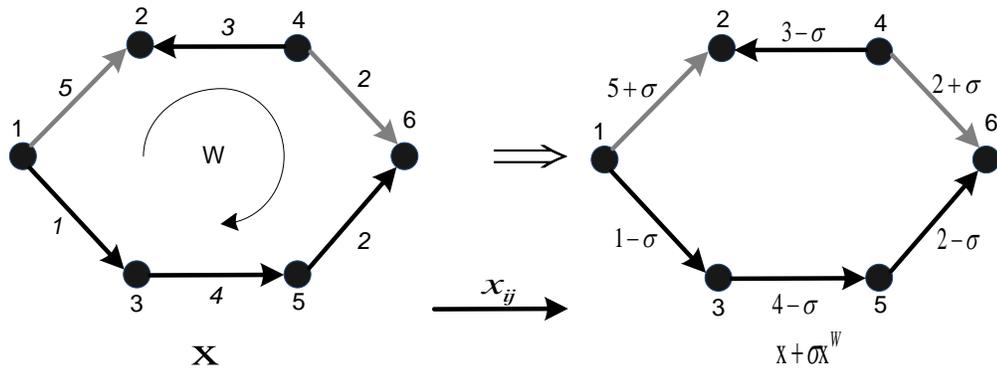


Figure 4 Augmenting flows around a cycle

Because the arc cost is flow dependent, denote by $c_W(x)$ the cost of cycle W at a given flow vector x . The cost of a cycle is the algebraic sum of the costs of all arcs contained in the cycle, i.e., $c_W(x) = c(x) * x^W = \sum_{(i,j) \in F(W)} c_{ij}(x_{ij}) - \sum_{(i,j) \in B(W)} c_{ij}(x_{ij})$. Its reversal cycle has $c_{-W} = -c_W(x)$. A cycle W has a capacity, denoted by $|W|$, which represents the maximum possible flow that can be sent around the cycle, without violation of flow non-negativity on any of the arcs in the cycle. $|W|$ equals the minimal flow value among $B(W)$, i.e., $|W| = \min\{x_{ij} | (i,j) \in B(W)\}$. If $B(W) = \emptyset$, then $|W|$ is infinite.

An arc (i,j) with $x_{ij} > 0$ is called an active arc; with $x_{ij} = 0$, it is called an inactive arc. A cycle W in which all of its backward arcs are active is called an active cycle (i.e., nondegenerate); otherwise, W is called an inactive cycle (i.e., degenerate). Note that W characterized by $B(W) = \emptyset$ is also an active cycle. An active cycle W implies $|W| > 0$, and thus, \exists a scalar $0 < \sigma \leq |W|$ such that one can augment σ units of flow on top of a feasible flow x such that $x + \sigma x^W$ remains feasible. A cycle in which all of its arcs, regardless forward or backward, are active is called a nonempty cycle. Obviously, a nonempty cycle must, at the same time, be an active cycle, but with a stronger condition. Hence, the set of nonempty cycles is a subset of the set of active cycles. A nonempty cycle implies both $|W| > 0$ and $|-W| > 0$; as a result, \exists a scalar $\sigma > 0$ such that one can send σ units of flow around either W or $-W$ without loss of feasibility.

2.4 Analytical formulation

Given a route flow vector $F = (f_r^{pq})_{r \in \mathcal{R}_{pq}, (p,q) \in V}$, Wardrop specified the user-equilibrium rule if the following route flow conditions hold for all OD pairs $(p,q) \in V$ (Patriksson 1994).

$$f_r^{pq} > 0 \Rightarrow c_r^{pq} = \pi_{pq} \quad \forall r \in \mathcal{R}_{pq} \quad (1a)$$

$$f_r^{pq} = 0 \Rightarrow c_r^{pq} \geq \pi_{pq} \quad \forall r \in \mathcal{R}_{pq} \quad (1b)$$

2.4.1 Optimization formulation of TAP

Suppose that the link travel time, $c = (c_{ij})_{(i,j) \in A}$, is a function of the flow on that link and that, furthermore, it is a nonnegative², monotonically increasing, and continuously differentiable function of the link flow. Although no explicit capacity constraint is imposed on the links, for proof convenience in this paper, we assume that the maximal flow assigned to an arc, and the maximal possible link travel time, are finite in a real instance. It is well known that TAP under the above assumptions is equivalent to the following standard convex optimization problem (Sheffi 1984):

$$\min Z = \sum_{(i,j) \in A} \int_0^{x_{ij}} c_{ij}(u) du \quad (2a)$$

s.t.

$$\sum_{r \in \mathcal{R}_{pq}} f_r^{pq} = d_{pq} \quad \forall (p, q) \in V \quad (2b)$$

$$f_r^{pq} \geq 0 \quad \forall (p, q) \in V, r \in \mathcal{R}_{pq} \quad (2c)$$

$$x_{ij} = \sum_{r \in \mathcal{R}_{pq}} \sum_{(p,q) \in V} f_r^{pq} \cdot \delta_{(i,j),r}^{pq} \quad \forall (i, j) \in A \quad (2d)$$

$$\delta_{(i,j),r}^{pq} = \begin{cases} 1 & \text{if route } r \text{ contains link } (i, j) \\ 0 & \text{otherwise} \end{cases} \quad (2e)$$

2.4.2 Formulation of origin-based TAP

Decompose the flow vector $x = (x_{ij})_{(i,j) \in A}$ to a set of commodities, i.e., $x = \sum_{p \in \mathcal{P}} x^p$, where each commodity $x^p = (x_{ij}^p)_{(i,j) \in A}$ represents the flow sourced from the origin p . TAP can be reformulated by using the origin flow, as follows (Bar-Gera 2002):

² Arcs with constant zero cost (e.g., centroid connectors) that form a cycle may become a concern. Here, we assume arcs with constant zero cost do not form a cycle.

$$\min Z = \sum_{(i,j) \in A} \int_0^{x(\mathbf{B}) + x_{ij}^p} c_{ij}(u) du \quad (3a)$$

s.t.

$$\sum_{(i,j) \in I(i)} x_{ij}^p - \sum_{(i,j) \in O(i)} x_{ij}^p = \rho_i^p \quad \forall i \in N, p \in \mathcal{P} \quad (3b)$$

$$\rho_i^p = \begin{cases} \sum_{q \in \mathcal{Q}(p)} d_{pq} & i = p \\ -d_{pq} & i = q \\ 0 & \text{otherwise} \end{cases} \quad \forall i \in N, p \in \mathcal{P}, q \in \mathcal{Q}(p) \quad (3c)$$

$$x_{ij}^p \geq 0 \quad \forall (i,j) \in A, p \in \mathcal{P} \quad (3d)$$

$$\mathbf{x}(\mathbf{B}) = \sum_{p' \in \mathcal{P} \setminus \{p\}} x_{ij}^{p'} \quad \forall (i,j) \in A, p \in \mathcal{P} \quad (3e)$$

In the design of an algorithm that loops among origins, x^p is the flow variable, and the flow originating from other origins, denoted by $x(\mathbf{B})$, is the constant background flow. When $x(\mathbf{B})$ is considered to be constant, formula (3) could also be deemed as the TAP on a single origin network. For an origin-based flow formulated in (3), we say that a flow vector meeting (3b) – (3d) is feasible.

To evaluate the traffic flow redistribution subject to roadway construction for repairing, replacing, or rehabilitating the concrete decks, the optimization formulations of TAP (2) and (3) need to be revised according to the involved work zones and/or reduced capacities needed for the construction. For various concrete technologies, their material properties are linked to the duration and frequency of roadway constructions. Especially, the unique characteristics of internally cured concrete enable the reduction in the frequency of repair and renewal that will significantly reduce the negative impacts on traffic flow due to roadway construction. The negative impacts on traffic flow can be evaluated by solving the TAP (2) or (3) with appropriate settings of capacity reduction in the model.

Solving the TAP efficiently is important in performing the life-cycle analysis of internal curing technique. The TAP needs to be solved multiple times to involve both short-term and long-term impacts on transportation network due to the required maintenance and replacement constructions in its life cycle. A computationally efficient algorithm will be helpful to calculate the costs associated with construction frequency and duration, and provide a more accurate estimate of network-wide impacts to traffic flows. Therefore, an efficient solution algorithm is developed to efficiently solve the TAP based on the origin-based UE formulation (3).

2.5 *Algorithm*

In this section, we design an algorithm that accomplishes the cycle optimality condition by operating a network simplex. The algorithm starts from any feasible solution: for example, from building a shortest path tree and sending flows from the source p to its destinations $Q(p)$ along the tree. Characterized by the “origin-based” feature, the algorithm loops among origins, treats flows originated from other origins as constant background flows and solves the single origin TAP repeatedly. The algorithm maintains feasibility throughout by augmenting flows on a set of active cycles that violate the cycle optimality condition. Augmenting flows on a negative cost active cycle improves the objective function without loss of feasibility. The algorithm continues until there is no negative cost active cycle in the network, which implies the single origin TAP is optimal due to Theorem 2. Note that the cycle optimality condition is verified if and only if the reduced cost optimality condition is verified, due to the equivalence of the two optimality conditions. The algorithm then proceeds to the next origin. The entire algorithm terminates when a pre-defined convergence criterion ϵ is reached – meaning a ϵ -UE is solved (Dial 2006).

The main task of the algorithm is to efficiently detect a negative cost active cycle. Accomplishment of this goal requires not only effective algorithmic design, but also efficient data structures. Unlike most known TAP algorithms, which utilize the shortest path tree more or less, we maintain a spanning tree structure for a fast detection of the cycles. Node potentials $\pi(\cdot)$ are computed by scanning in-tree arcs from the root, visiting each node in a depth-first search. The reduced cost of an in-tree arc $(i, j) \in \mathcal{T}$

(also called a basic arc) has $c_{ij}^\pi = 0$; the reduced cost of an out-of-tree arc $(i, j) \notin \mathcal{T}$ (also called a non-basic arc) is computed by $c_{ij}^\pi = c_{ij}(x_{ij}) + \pi_i - \pi_j$.

Due to the reduced cost optimality condition, if all non-basic arcs admit

- i. $c_{ij}^\pi \geq 0$, or
- ii. $c_{ij}^\pi = 0$ and $x_{ij} > 0$,

such a feasible flow vector is an optimal solution to the single origin TAP. Any arc violating (i) or (ii) must have $c_{ij}^\pi \neq 0$; adding it in the tree forms a cycle W (pivot cycle) with $c_W(\mathbf{x}) \neq 0$. If $c_W(\mathbf{x}) < 0$ we detect a negative cost cycle $W_o := W$; if $c_W(\mathbf{x}) > 0$, we also detect a negative cost cycle $W_o := -W$. Theorem 2 suggests sending flows around W_o to improve the cost of the pivot cycle if doing so is feasible (i.e., W_o is active). The maximal flow that one can send around W_o is bounded by $|W_o|$. Consider the following two cases of pseudoflow \mathbf{x}' by sending the maximal possible flow around W_o , i.e., $\mathbf{x}' := \mathbf{x} + \sigma \mathbf{x}^{W_o}$; $\sigma = |W_o|$. Case 1: $c_{W_o}(\mathbf{x}') < 0$. W_o becomes inactive at \mathbf{x}' . To continue the algorithm, the tree must be updated. Case 2: $c_{W_o}(\mathbf{x}') > 0$. Since any augmentation of $0 < \sigma < |W_o|$ units of flow would make W_o a nonempty cycle, we should augment σ units of flow such that $c_{W_o}(\mathbf{x}') = 0$ due to Corollary 2. The only special case is that augmenting $\sigma = |W_o|$ units of flow right makes $c_{W_o}(\mathbf{x}') = 0$, where we maintain both $c_{W_o}(\mathbf{x}') = 0$ and W_o is inactive. Overall the method is to compute σ such that $c_{W_o}(\mathbf{x}') = 0$, and to augment $\min\{\sigma, |W_o|\}$ units of flow around W_o to ensure that either $c_{W_o}(\mathbf{x}')$ equals zero, or $c_{W_o}(\mathbf{x}')$ is negative and W_o is inactive.

The overview of the negative cost cycle cancellation method could be stated as follows.

- a. Identify a non-basic arc (i, j) violating (i) or (ii), and add (i, j) into \mathcal{T} to construct a cycle W (W is with the same direction as (i, j)), compute $c_W(\mathbf{x})$;
- b. If $c_W(\mathbf{x}) < 0$, $W_o := W$; if $c_W(\mathbf{x}) > 0$, $W_o := -W$ (pivot cycle);
- c. If $|W_o| > 0$, compute σ such that $c_{W_o}(\mathbf{x} + \sigma \mathbf{x}^{W_o}) \approx 0$ (line search); otherwise go to e;
- d. $\theta := \min\{\sigma, |W_o|\}$; update flow vector $\mathbf{x} := \mathbf{x} + \theta \mathbf{x}^{W_o}$ (flow augmentation);

- e. If an arc $(m, n) \in \{B(W_o) \cap \mathcal{T}\}$ is inactive at the new flow vector \mathbf{x} , replace (m, n) by (i, j) in \mathcal{T} ;
- f. The procedure continues until no non-basic arcs violating (i) or (ii), meaning optimum;
- g. Proceed to next origin, repeat (a) – (f).

Computing σ is called a line search. Because the cost function of an arc is non-linear, one can use the Newton method to linearize the cost function, as suggested in (Dial 2006).

$$c_W(\mathbf{x} + \sigma \mathbf{x}^W) =$$

$$\sum_{(i,j) \in F(W)} c_{ij}(x_{ij} + \sigma) - \sum_{(i,j) \in B(W)} c_{ij}(x_{ij} - \sigma) \approx \sum_{(i,j) \in F(W)} c_{ij}(x_{ij}) + \sigma \cdot$$

$$\sum_{(i,j) \in F(W)} c'_{ij}(x_{ij}) - \sum_{(i,j) \in B(W)} c'_{ij}(x_{ij}) + \sigma \cdot \sum_{(i,j) \in B(W)} c'_{ij}(x_{ij}) = 0;$$

$$\Rightarrow \sigma \approx \frac{-c_W(\mathbf{x})}{\sum_{(i,j) \in F(W)} c'_{ij}(x_{ij}) + \sum_{(i,j) \in B(W)} c'_{ij}(x_{ij})},$$

where $c'_{ij}(x_{ij})$ is the derivative of $c_{ij}(x_{ij})$ w.r.t. \mathbf{x} .

2.6 Algorithm implementation

2.6.1 *Data structure of the algorithm*

An efficient data structure is critical to the success of the proposed algorithm. Over the years, researchers have suggested several procedures for maintaining and manipulating a spanning tree for an efficient algorithm design. The Parent-Thread-Depth scheme is one of the most powerful three-label data structures for implementing the proven fast network algorithms. Parent is designed to store a spanning tree structure; Depth is for the ease of detecting a cycle, and manipulating one spanning tree to another, and Thread is designed for a fast visit of all of the descendants of a node in recalculating node potentials.

For the basic MCF, node potentials need to be recalculated in an efficient manner after each flow augmentation. In the TAP, the travel cost is a non-linear function of the link flow, and it could take many iterations to reach the equilibrium. Because we do not

update the node potentials in every flow augmentation as in MCF, updating node potentials by visiting an entire spanning tree perhaps is less expensive than maintaining a Thread for every flow augmentation, for which the manipulation is rather involved. In our algorithmic design, we apply the Parent-Thread-Depth structure in (Bazaraa et al. 2009) without using the Thread.

2.6.2 Convergence criterion

There are several methods for measuring the convergence of the TAP. The Relative gap (RG) is a commonly used stop criterion.

$$\text{RG} = \frac{\sum_{p \in \mathcal{P}} \sum_{(i,j) \in A} x_{ij}^p c_{ij} - \sum_{p \in \mathcal{P}} \sum_{(i,j) \in A} x_{ij}^p (d_j^p - d_i^p)}{\sum_{p \in \mathcal{P}} \sum_{(i,j) \in A} x_{ij}^p c_{ij}} \quad (4)$$

where d_i^p denotes the shortest distance from the root p to i . RG requires computing the shortest path trees, which is usually not an extra task because it is a required intermediate step for most existing TAP algorithms. The algorithm proposed in this paper, however, does not compute the shortest path trees during the intermediate steps; therefore, computing RG would impose extra resources and running time. To measure how close a flow vector is to UE, we utilize the gap function computed on the tree, which is denoted by the relative gap on the tree (TRG), as follows.

$$\text{TRG} = \frac{\sum_{p \in \mathcal{P}} \sum_{(i,j) \in A} x_{ij}^p \cdot \text{abs}(c_{ij}^\pi) + \sum_{p \in \mathcal{P}} \sum_{(i,j) \in A | x_{ij}^p = 0, c_{ij}^\pi < 0} (-c_{ij}^\pi)}{\sum_{p \in \mathcal{P}} \sum_{(i,j) \in A} x_{ij}^p c_{ij}} \quad (5)$$

where $\text{abs}(c_{ij}^\pi)$ denotes the absolute value of c_{ij}^π . The term $x_{ij}^p \cdot \text{abs}(c_{ij}^\pi)$ measures the severity of the violation of the complementary optimality condition on an active arc, and the term $-c_{ij}^\pi$ measures the severity of the violation on an inactive arc. Both origin-based flow x_{ij}^p and reduced cost c_{ij}^π can be obtained in the intermediate computations, without extra computational effort. $\text{TRG} = 0$ if and only if x^p is optimal for every p , due to the reduced cost optimality condition. Furthermore, if the spanning tree is the shortest path tree, then $\text{TRG} = \text{RG}$.

2.6.3 Pivot rule

The selection of entering and leaving arcs for generating a new basis involves different rules, called pivot rules. Pivot rules have been extensively studied in the MCF,

which have significant impacts on the number of pivots that the algorithm encounters. In the MCF, even proven finitely convergent, the network simplex could experience an exponential number of consecutive degenerate pivots without cycling, a phenomenon known as stalling (Cunningham 1979). Specific choices for the pivot rules can prevent both cycling and stalling (Cunningham 1979), or can lead to a polynomially bound number of pivots for specific problems (Orlin 1985). Therefore, pivot rules for the proposed algorithm could be an intensive topic.

The pivot rule implemented in this paper leverages the known results of the MCF. Specifically, we adopt Danzig's rule, which chooses the non-basic arc with the largest violation to be the incoming arc. The violation of an eligible non-basic arc is measured by $\text{abs}(c_{ij}^\pi)$. We sort $\text{abs}(c_{ij}^\pi)$ of non-basic arcs in the arc-eligible list in a decreasing order, and then, we add those arcs into the tree one by one following the same decreasing order. In a degenerate pivot, we select the leaving arc as per (Cunningham 1976), as discussed in §4. If SFSTs are maintained, then the pivot rule guarantees the finite convergence.

2.6.4 *Summary of the algorithm*

The overall design of an efficient implementation is a key to the success of the algorithm. The most computationally expensive step is to update the reduced cost. In a large-scale network, it is not unusual to involve hundreds of thousands of links; thus, one pass of scanning arcs to update the reduced cost is expensive. In an efficient implementation, we are motivated to reduce updates of reduced costs to the minimum possible.

The implementation is designed as follows. Before trees reach convergence, we update π , c^π and the arc-eligible list immediately, because the arc-eligible list would change significantly in the next iteration. After the trees converge, we continue sending flows under the same set of the arc-eligible list for several iterations, before proceeding to rebuild the arc-eligible list. This design is similar to the restricted master problem implemented in a bush-based algorithm, which repeatedly solves a restricted master problem on a given bush, until the solution converges to reach a desired stop criterion and then proceeds to update the bush. Operating flows on a spanning tree restricted to

the given set of arc-eligible list is the restricted master problem counterpart in our algorithm. Without loss of generality, we use an arbitrary rule of $\text{TRG} < 1e - 2$ to roughly justify that the trees have converged. When $\text{TRG} \leq 1e - 2$, we do not update π and c^π and not rebuild the arc-eligible list until the restricted master problem is solved k times (see the flowchart in Figure 5).

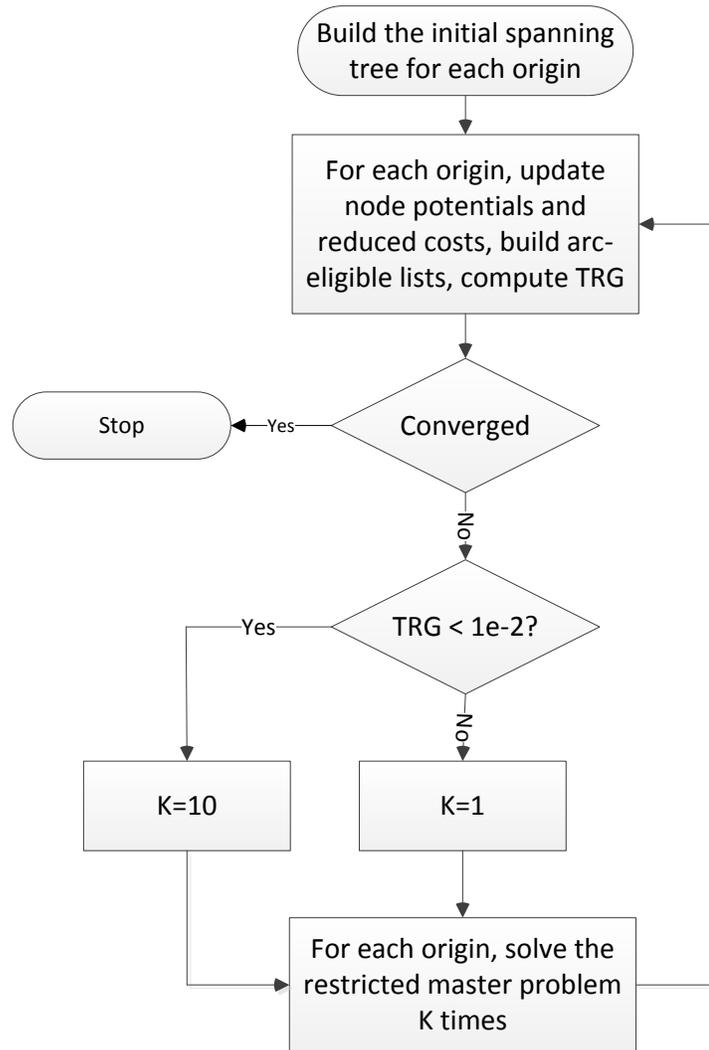


Figure 5 Flow chart of the implementation

Note that in the implementation, one more step is required to verify whether the incoming arc remains eligible or not. Suppose that (k, l) is the entering arc in a pivot; its reduced cost and flow might already change because of operating flows on other sources or in previous iterations. The true reduced cost wrt the updated flow vector always equals c_W . For example, suppose that (k, l) is added into the arc-eligible list with

$c_{kl}^\pi < 0, x_{kl} = 0$, but after operating flows for other origins, and for eligible arcs ranked higher than (k, l) , the pivot cycle identified by adding (k, l) may have $c_W > 0$. It implies the true reduced cost changes to positive already, if $x_{kl} = 0$ still holds, (k, l) is not eligible to enter the basis according to the reduced cost optimality condition.

2.7 Test network

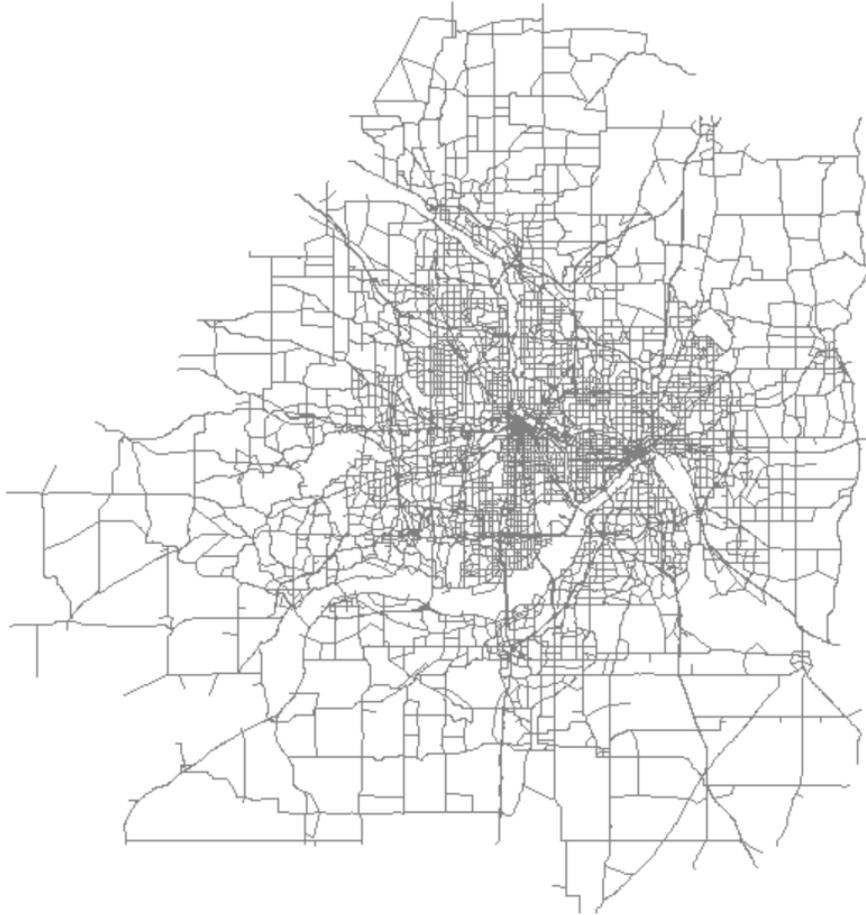


Figure 6 Minneapolis-Saint Paul metropolitan highway network

We perform a case study on a real-world transportation network of Minneapolis-Saint Paul metropolitan area, which is the one of the most populated urban areas in the U.S. state. The skeleton structure of the conflated planning network, which covers seven counties of Minneapolis-Saint Paul metropolitan area, is shown in Figure 6. This network contains 22,476 links and 8,618 nodes, of which 1201 are traffic analysis zones (TAZs) that generate and attract trips. A fixed demand table is used in the traffic

assignment problem to analyze the impacts of internally cured concrete on traffic flows. A trip table, derived from the 2005 Longitudinal Employer-Household Dynamics (LEHD) database³, is adopted as the origin-destination demand data.

2.8 *Construction scenario*

The impact study⁴ was carried out following one subproject of I-35E corridor projects in city of Minneapolis. I-35E corridor project is one of five major projects in state of Minnesota. It contains three major subprojects, including Cayuga project, MnPASS project and Maryland project. The benefits of the I-35 corridor project is to replace bridges currently on the State's Chapter 152 list (Trunk Highway Bridge Improvement program Chapter 152), provide line-of-sight improvements for the interchanges and I-35E (safety and operation improvements), provide better interchange spacing between Maryland Ave and University Ave by shifting the interchange from Pennsylvania Ave to Cayuga Street, provide improved access for St. Paul's Phalen Boulevard, and MnPASS lanes will offer reliable travel options for public and can move 50 percent more traffic than regular lanes during congested rush hour periods. This subproject belongs to I-35E MnPASS and the lanes closure is following the anticipated schedule between mid-June and mid-October. The purpose of this project is to add new MnPASS express lanes on both directions of I-35E, long-term pavement improvement between little Canada Road and Maryland Avenue, replace Arlington, Wheelocak and Larpenteur bridges, and replace I-35E bridge spanning Roselawn Avenue. The expected closing time will be approximately mid-June to mid-October. The traffic related impacts are listed in Table 4 and the details of the impact area can be found in Figure 7.

In May 2005, Minnesota began the operations of an 11-mile high occupancy/toll lane (HOT) along I-394 West. It was the first high occupancy vehicle lane (HOV)-to-HOT lane conversion in Minnesota and was named the MnPASS lane. Despite the high costs of HOV-to-HOT lanes construction, a 2005 MnPASS study confirms the success of the MnPASS lanes in reducing congestion and both MnPASS users and non-users thought positively of the I-394 MnPASS lane, and the extension of the HOT lanes has

³ Downloaded from: <http://www.vrdc.cornell.edu/onthemap/data>

⁴ Project details can be found via <http://www.dot.state.mn.us/metro/projects/35estpaul/>

been entertained (Munnich, 2008). Minnesota Department of Transportation (MDOT) in charge of overseeing the overall planning and implementation of the program.

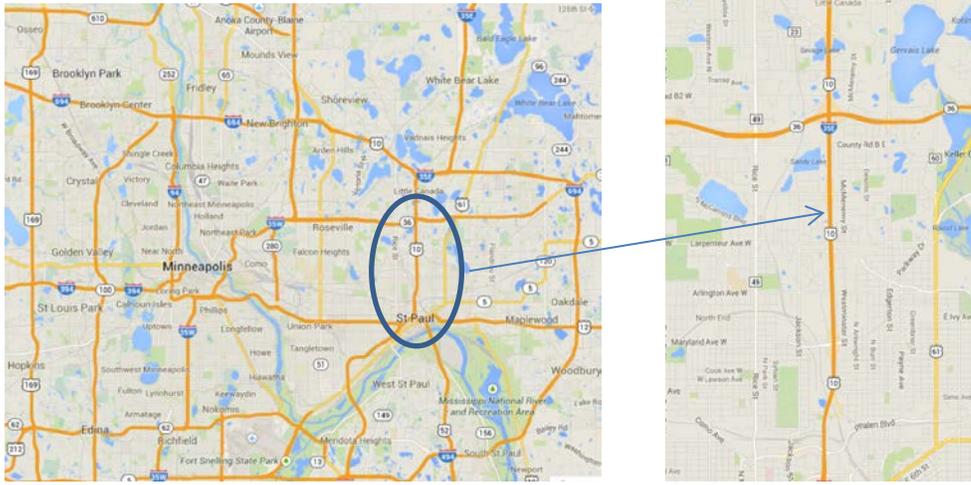


Figure 7 Minneapolis-Saint Paul network project area

Table 4 Impacts on the traffic

Location	Action
I-35E between Little Canada Rd and Maryland Ave	Two lane for each direction
Ramp from Maryland Ave to northbound I-35E	Close
Ramp from northbound I-35E to Roselawn Ave	Close
Ramp from Roselawn Ave to northbound I-35E	Close
Ramp from Roselawn Ave to southbound I-35E	Close
All ramps and loops at the I-35E/Hwy 36 interchange, except the ramp from southbound I-35E to westbound Hwy 36	Close
Ramp from northbound I-35E to Little Canada Rd	Close
Ramp from little Canada Rd to southbound I-35E	Close

To calculate the total travel time increase for the system, we compared the travel time before and during the project by conducting traffic assignment. The details of the traffic assignment will be provided in previous chapter. The profile of the network is changed based on the same changes made in the project by adjusting the link capacity and free flow travel time. The network at the project impact location is provided in

Figure 7. The average computing time for traffic assignment is around 4.5 minutes. Based on the available data, the anticipated peak hour total network delay is 343.17 hrs for this subproject.

2.9 Value of travel time savings

One of the critical elements in benefit-cost analyses of transportation projects are the estimates of value of travel time (VOT) and the value of travel time savings (VTTS). The concept related to the value of travel time is extensive and well developed. A study done by Lam and Small (2001) estimated the average VOT to be \$22.87 per hour, or 72 percent of average wage rate. Using the revealed preference data on trips taken on I-95 along the 95 along the 95 Express corridor, the estimated VTTS of travelers is approximately 49 percent of their hourly wage based on annual household income, with a range of \$2.27 to \$79.32 per hour and a mean of approximately \$32.00 per hour (Perk, et al., 2011). A recent study done by Burris and Danda (2014) concludes that the values of travel time of \$2.60/hour, \$8.63/hour, and \$10.71/hour for off-peak, shoulder, and peak period travelers on Katy freeway in Texas.

In the context of this project, the value of time for drivers is \$10.61/hour based on the study done by Carrion, et al. (2012) for commuters in Minneapolis. This value is similar to the peak period VOT for drivers in Texas. By applying the similar scale to drivers in Minneapolis, their off-peak and should VOT is \$2.58/hour and \$8.55/hour respectively. As a result of the total user cost increase during the construction period is \$3641.03/hour during the peak hour.

2.10 Life-cycle cost comparison of conventional concrete mixture and internally cured concrete mixture

Comparing to normal concrete decks, a recent study done by Cusson et al., (2010) show that 10%, 25% and 50% probabilities of spalling were reached after 9, 14, and 22 years. For the high performance concrete and high performance internally cured concrete decks, these threshold probabilities were reached after 15, 25, and 40 years; and 24, 39 and 63 years, respectively. The time-dependent probability of concrete over spalling is provided in Figure 8.

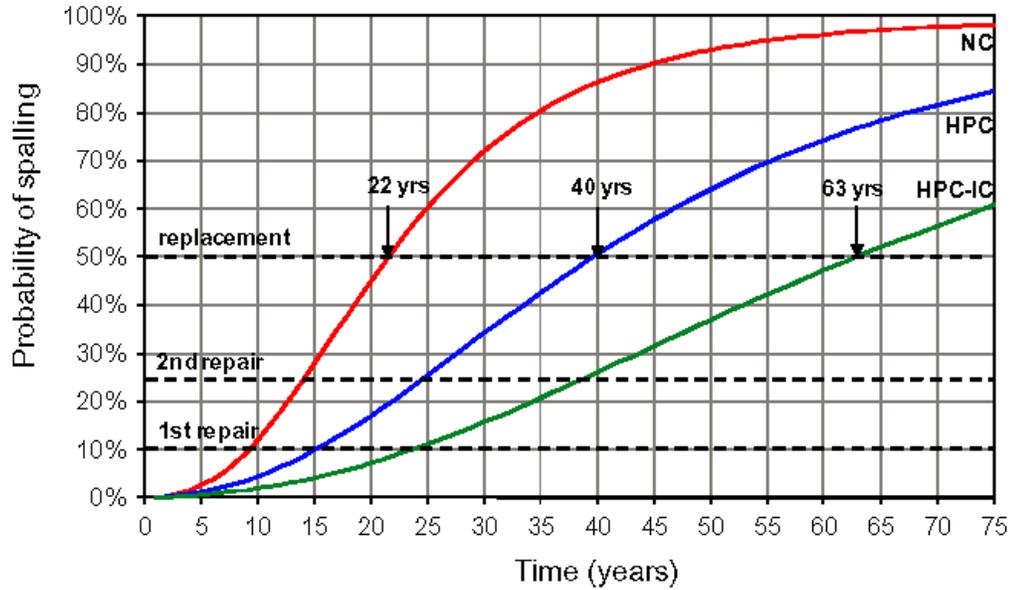


Figure 8 Probability of concrete cover spalling (Cusson et al., 2010)

In the total life-cycle cost, the following costs were considered, agency costs, user costs, and environmental costs. The agency costs represent the costs applied to transportation agency on bridge deck construction, inspections/maintenance, repair and rehabilitation costs in the costs analysis period. The user costs consist of costs increase due to the traffic disruption caused by bridge deck related projects. In this context, operation costs increase, value of travel time costs and safety costs were considered. The auto vehicle operating cost is \$0.32/mile and the occupant value of time \$13.93/hour and both of these values came from MnDOT for estimation of 2010. For increased traffic crash related to construction work zones and increased distance traveled when detours are used to avoid construction zones also contribute to user costs. In 2013, the result is an estimated \$0.17 per vehicle mile traveled (VMT) in the construction zone, and \$0.07 per VMT traveled when a detour is taken. Assuming a 60 years of study period, the present value of life-cycle costs (PVLCC) can be written as,

$$PVLCC = C_0 + \sum_{t=1}^T \frac{C_i}{(1+r)^t} - \frac{R_v}{(1+r)^T}$$

where C_0 is the initial construction cost; C_i is the i th expenditure at given time t (years); R_v is the residual value of the alternative at the end of the analysis period; and T is the analysis period (years).

The unit cost of HPC ($\$600/\text{m}^3$) was estimated to be 33% higher than conventional concrete (CC) ($\$450/\text{m}^3$). The unit cost of HPC-IC was set to that of HPC plus a 4% increase to account for the cost different associated purchase and transportation. These costs were adopted from Cusson et al., (2010) paper. Table 5 summarized the information related to different unit costs and all these information are in Year 2014 dollars. Air pollution costs were not included in this study, as it only represents a small portion of the total life-cycle costs based on previous studies.

Table 5. Costs of different activities/materials in 2014 U.S. dollar

Activity type	Cost in 2014 U.S. dollar
<i>Costs of maintenance related activities (agency costs)</i>	
Routine inspection ($\$/\text{m}^2$)	2.18
Non-destructive evaluation ($\$/\text{m}^2$)	21.82
Protection ($\$/\text{m}^2$)	21.82
Patch repair ($\$/\text{m}^2$)	218.20
Replacement (disposal and reconstruction) ($\$/\text{m}^2$)	381.85 + unit costs of reconstruction
<i>User costs at the time of construction/maintenance related activities (user costs)</i>	
Auto vehicle operating cost is $\$/\text{mile}$	0.35
Occupant value of time	15.20
Average occupant per vehicle	1.07
User safety costs at construction zone ($\$/\text{VMT}$)	0.17
User safety costs for taking detour ($\$/\text{VMT}$)	0.07
<i>Initial construction costs (agency costs)</i>	
Unite cost of CC ($\$/\text{m}^3$)	490.95
Unite cost of HPC ($\$/\text{m}^3$)	654.61
Unite costs of HPC-IC ($\$/\text{m}^3$)	680.79

In Figure 9, three different fixed schedule of maintenance/replacement plan for three different materials are presented. For various maintenance activities were assumed to take place on bridge decks, the assumption is routine inspections at two year intervals,

non-destructive evaluation and protection activities occur every 5 years. For protection activities, a two-month maintenance project is assumed by closing one lane at each direction. Major patch repairs were scheduled at the time of 10% and 25% of the deck surface. At the time of patch repairs, an eight-month two-lane closure at each direction is assumed. In this study, an estimated 3.26 kilometers project on I-35E is studied. In this project, two highway bridges are involved as one 0.4 miles (644 meters) long and one 354 ft (108 meters) long. Both bridges are highway bridge decks with 3-lane at each direction.

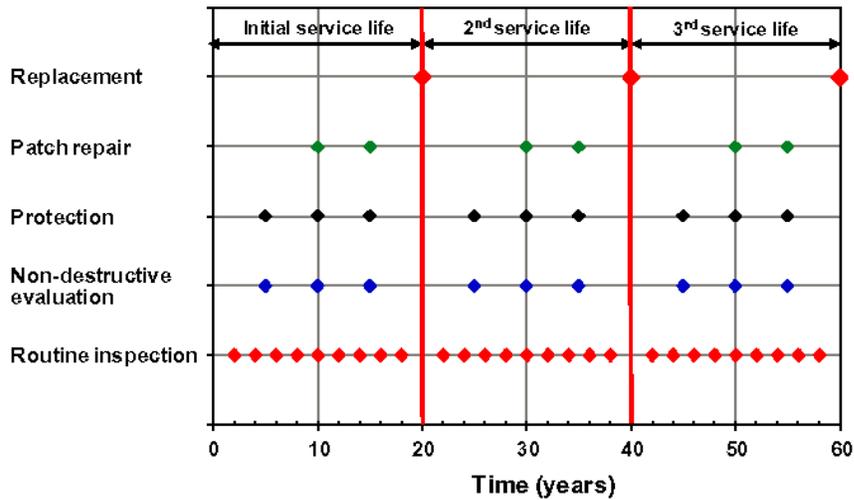


Figure 9a. Optimised maintenance schedules for normal concrete deck alternative

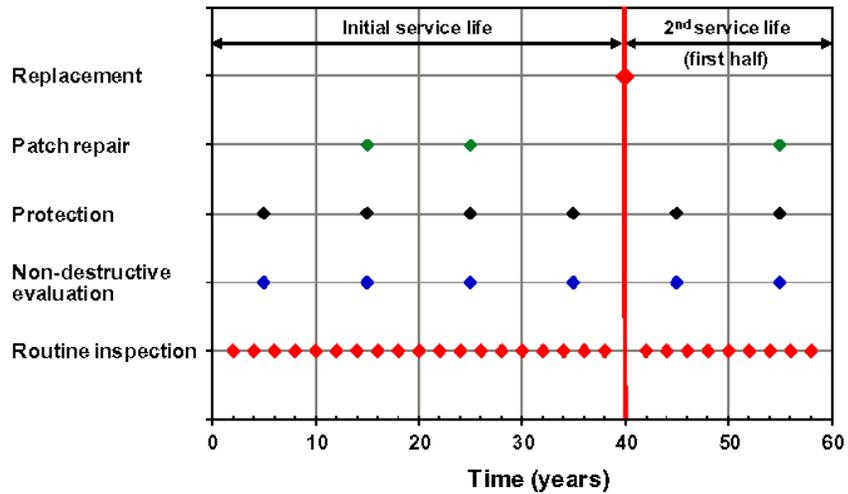


Figure 9b. Optimised maintenance schedules for HPC deck alternative

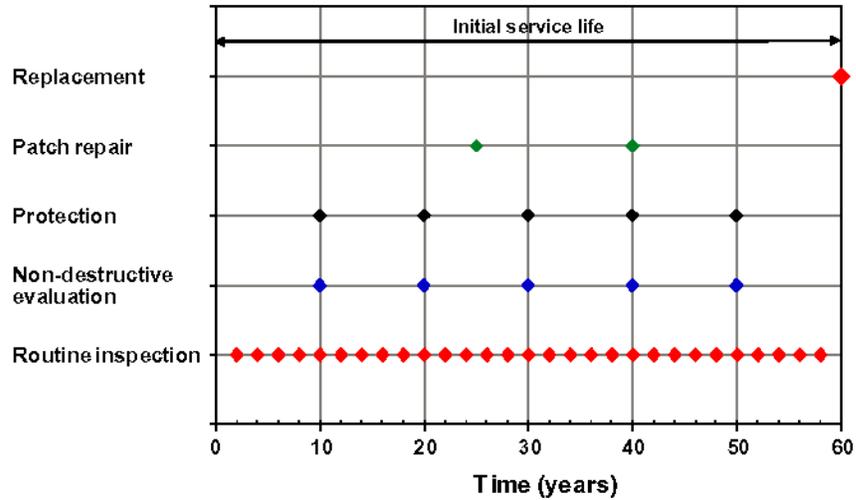


Figure 9c. Optimised maintenance schedules for HPC-IC deck alternative

In Figure 10, the present value of cumulative expenditure is summarized. The potential total life-cycle cost of HPC-IC savings comparing to conventional concrete bridge deck can be as high as 71%, and 48% over HPC in a 60-year analysis period.

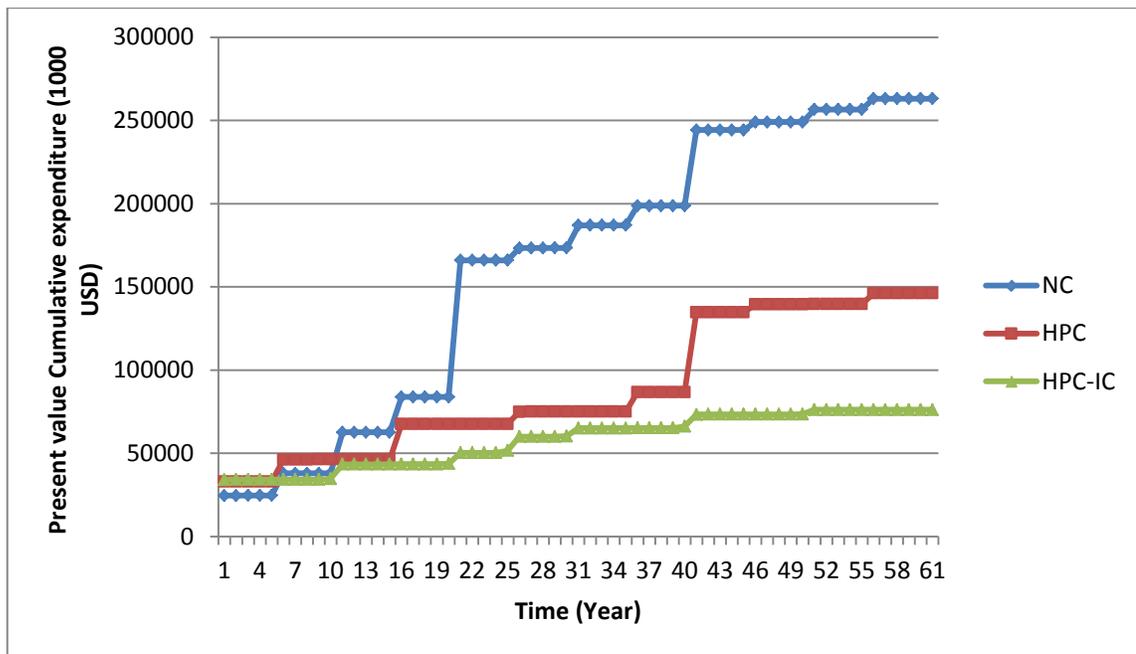


Figure 10. Present value (2014) of cumulative expenditure for all bridge deck alternatives.

CHAPTER 3. CONCLUSIONS

3.1. Summary

The data from internally cured commercial concrete used in field structures to estimate the service life of reinforced concrete bridge decks by using a methodology of which accounts for the mixture proportions, the permeability, and the intrinsic chloride diffusion of a concrete mixture while simulating the regional field exposure conditions of a bridge deck made with these materials. The results indicate that the effect on permeability of internal curing may be associated with the volume of voids present from air entrainment. Additionally, internal curing generally results in a significant reduction in the tortuosity of the concrete, due in part to the extended degree of hydration and the densification of the interfacial regions around the LWA. It was shown that for the service life model presented herein the IC HPC concretes cast in the state of Indiana in 2013 achieve an estimated service life improvement of 3 to 4.5 times that of the conventional bridge deck concrete specified, while a field inspection of one of these bridges indicated no visible shrinkage cracking 18 months after casting.

Based on the total life-cycle cost study, IC-HPC can significantly reduce the costs comparing to HPC and conventional concrete mixture in bridge deck. The case study of a construction project located in St. Paul of Minnesota, our results show that IC-HPC can reduce more than 70% of total life-cycle costs of conventional concrete mixture. The largest cost reduction comes from user costs, because IC-HPC can significantly reduce the number of maintenance scheduled in the project life-cycle.

The key contributions of this study are that a holistic perspective is proposed to quantify the potential benefits of internally cured concrete mixtures compared to

conventional mixtures in a transportation system. A nonlinear programming model is developed to evaluate the total life-cycle costs of internally cured highway bridge decks, in term of construction costs, user costs, and environmental costs. This model can help planners in designing effective and sustainable replacing and repair mechanisms in high traffic areas.

3.2. Future research direction

The analysis based on the data from the optimized maintenane shedules is still required more on the environmental costs and the potential future traffic volume increase. In addition, additional information related to different maintenance planning and implementation methods should be tested in order to improve the study analysis. Finally, there is a need to further develop analytical models to identify the optimal repair and replacement approaches to maximize the long-term total life-cycle savings of internally cured highway bridge decks.

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