Emission-controlled pavement management scheduling

U. D. Tursun, R. Yang, I. L. Al-Qadi
University of Illinois Urbana–Champaign, IL, USA

ABSTRACT: This paper describes an analytic approach that can be used to evaluate and propose rehabilitation schedules based on economic, performance, and environmental considerations for various types of pavements managed by the Illinois State Tollway Authority. A mixed-integer nonlinear program (MINLP) is formulated to model the agency's life-cycle cost and environmental impacts where the decision set consists of the maintenance overlay type and the thickness of the overlay proposed on a temporal scale over a planning horizon. The problem requires interaction of the integer and continuous variables that leads to MINLP formulation. Considering practical implications of the problem, the continuous variables are bounded into a finite and discrete set, while the integrality constraints are relaxed. The objective and constraints of the problem can be alternated to suit the needs of the agency, which may be interested in minimizing environmental impacts and restricting the cost to the agency, or vice versa, over the pavement life-cycle.

Keywords: Mixed-Integer Nonlinear Programming, Sustainability, Pavement Management

1 PAVEMENT MANAGEMENT SCHEDULING

1.1 *Introduction*

Although transportation agencies traditionally have considered cost as the main factor in deciding initial pavement design and maintenance schedules, interest in evaluating environmental impacts of transportation infrastructure has become common. In a 2011 survey, it was found that 29 out of 35 responding state departments of transportation (DOTs) in the United States perform life-cycle cost analysis (LCCA) to evaluate alternative pavement designs for new construction and reconstruction projects (Hallin et al. 2011). Thus, both the initial cost of construction and the future cost of expected maintenance and rehabilitation (MR) schedules over the lifetime of the pavement are considered.

The parallel approach to LCCA for environmental consideration is life-cycle assessment (LCA), which is not currently implemented by any US state DOT. Similar to LCCA, this methodology evaluates the environmental impacts incurred over the entire pavement life cycle from initial construction, MR, use, and disposal. If combined, LCCA and LCA result in quantitative cost and environmental measures, respectively, that can systematically inform an agency's decision-making process.

As LCCA is already an established component of pavement management, recent literature has investigated the application of LCA to pavement management and, specifically, how cost and environmental concerns can be balanced. Gosse et al. (2012) used a multi-objective genetic algorithm able to develop Pareto sets of maintenance plans in Virginia for various budgets, pavement performances, and emission levels. The scope of the work included only materials and construction, taking into account the deterioration of the pavement without user emissions or costs. Yu et al. (2013) further integrated LCA and LCCA for three types of overlay systems by using dynamic programming to consider both agency and user emissions, as well as costs from construction, work zone delay, and normal use of the pavement. Optimized strategies for each overlay system were developed by minimizing life-cycle cost, as well as environmental impacts (greenhouse gases, GHGs; and energy). Lidicker et al. (2012) in turn evaluated resurfacing policies based on minimizing life-cycle costs and emissions from both the user and the agency to find optimal overlay intervals (i.e. 15 years for minimum GHGs and 22 years for minimum cost).

Bryce et al. (2014) and Reger et al. (2014) applied optimization techniques at a multifacility level, incorporating pavement segments from a large network. Bryce et al. included various levels of MR treatment types, and also incorporated probabilistic distributions to account for uncertainties in the extent of treatment (e.g. thickness of overlays), transportation distances, and per unit environmental impact values themselves. A Pareto set for a network was given with respect to cost, energy, and pavement condition. Reger et al. minimized equivalent annual agency costs for a network while constraining GHGs. A Pareto set was formed and used to evaluate past and present MR policies in California. An updated study by Reger et al. (2015) also considered constraining the agency budget and minimizing emissions. In the network-level studies mentioned, delay effects from the work zone during construction was omitted.

Overall, a number of approaches have been implemented to integrate economic and environmental concerns into pavement management. However, this study extends the literature by including probabilistic consideration of changing traffic levels over time, updated inventory, and models specific to the targeted agency.

Transportation agencies have focused on material and process selection to reduce the environmental impacts of maintenance activity (Zapata & Gambatese 2005, Santero & Horvath 2009). Some of the applied environmental impact rating tools at the individual-project level are the Greenroads tool, the infrastructure voluntary evaluation sustainability tool (INVEST) from the Federal Highway Administration (FHWA), and the Illinois livable and sustainable transportation system (ILAST). Yet comprehensive, practical, and computationally tractable algorithms that would allow transportation agencies to add an environmental dimension to current pavement management systems (PMSs) while reducing total economic impact and attaining performance targets are still not in place.

Many optimal decision problems in areas such as logistics, manufacturing, transportation, and the chemical and biological sciences involve both continuous and discrete decision variables over nonlinear system dynamics that require mixed-integer nonlinear programming (MINLP). The MINLP class of problems combines the combinatorial difficulty of optimizing over discrete variable sets, namely the mixed-integer linear programming (MILP), with the challenges of handling nonlinear programming (NLP). Nonlinear programming algorithms usually resort to certain convexity assumptions, leading to local optimization guaranteeing the global optimum. Without convexification, identifying a global optimum in the presence of multiple local optima is not guaranteed. Even when the objective function is convex, nonlinearities in the constraint set may give rise to local optima. Mixed-integer nonlinear programming entails optimization problems where the objective and/or constraints are nonlinear, with continuous and integer variables. MINLPs are a particularly challenging class of optimization problems. Even having only linear functions or merely continuous variables, which reduces MINLP into mixed-integer linear problems (MILPs) or nonlinear problems (NLPs), respectively, does not ease the computational intractability issues (Murty & Kabadi 1987, Garey & Johnson 1979). There have been efforts to solve a subclass of deterministic MINLPs, where the objective function and constraints are convex and upper-bounded (Gupta & Ravindran 1985, Quesada & Grossmann 1992a). When integer variables of MINLPs are relaxed, the feasible set is bound to be convex. Convex optimization on continuous variables has some strong advantages due to necessary and sufficient optimality conditions, duality theory, and reliable algorithms for reasonably large subclasses of these problems.

The literature has algorithms to generate and refine bounds on the optimal solution value of a convex MINLP with a finite number of constraints Bonami et al. (2012). A tree-search algorithm similar to a branch-and-bound algorithm was proposed by Dakin (1965) for convex MINLPs. Later, a generalized Benders decomposition by Geoffrion (1972) in which the parametrized subproblem of classical Benders decomposition was offered. Convex duality theory is used to derive the natural families of cuts corresponding to those in Benders' case. An outer-approximation algorithm was first presented by Duran & Grossmann (1986) for the same class of problems. Based on principles of decomposition, outer-approximation, and relaxation, the proposed algorithm consists of solving an alternating finite sequence of nonlinear programming subproblems and relaxed versions of a mixed-integer linear master program. The same algorithm was further improved by Fletcher & Leyffer (1994). An LP/NLP-based branch-and-bound algorithm in which the explicit solution of an MILP master problem is avoided at each major iteration in the framework of an outer-approximation algorithm was proposed by Quesada & Grossmann (1992b). Based on the algorithms proposed so far, the convex MINLP is broken into two pieces, MILP and NLP, which are solved separately.

The formulated MINLP problem that we solve is transformed into a pure integer problem where the continuous variables are bounded into a finite and discrete set. Also relaxing the integrality constraints leads to a convex formulation that can be solved with commercial solvers.

First of all, objective of this study is explained in section 1.2. In section 2, problem formulation and solution methodology including the details of Monte Carlo simulation is presented. And the paper is concluded by reporting the results of analysis and discussion of future direction.

1.2 *Objective*

A transportation agency typically utilizes a PMS to plan rehabilitation operations by identifying schedules based on pavement condition, subject to cost constraints. Current PMSs of the Illinois State Tollway Authority (Illinois Tollway) do not typically incorporate environmental considerations into the decision-making process to balance performance and environmental goals. This work seeks to develop a practical and computationally tractable algorithm that would allow Illinois Tollway to add an emission-control objective to the current goals related to cost and condition of pavement.

2 MIXED-INTEGER NONLINEAR FORMULATION OF EMISSION-CONTROLLED MAINTENANCE SCHEDULE

Our goal is to evaluate and propose maintenance schedules for various types of pavement for the Illinois State Tollway Authority, based on economic, performance, and environmental considerations. A mixed-integer nonlinear problem is formulated to model the life-cycle cost to the agency and the greenhouse gas emission due to both user and maintenance activities of a single pavement segment. There are two opposing motivations within each section of the objective function. While an increase in the International Roughness Index (IRI) value causes a linear surge in user emission, scheduling an overlay to lower the IRI value also leads to further emission due to construction activity. The decision set consists of maintenance type and thickness of overlay over the lifetime of the pavement. The problem requires interaction of integer and continuous variables within nonlinear equations leading to MINLP formulation. The inclusive mathematical formulation of the mixed-integer nonlinear problem is expressed as:

$$
\begin{aligned}
(P) \qquad & \min f(x,y) \\
\text{s.t.} \quad & \\
& g(x,y) \leq 0 \\
& x \in X \subseteq \mathbb{Z}^p \\
& y \in Y \subseteq \mathbb{R}^n,
\end{aligned}
$$

where $f:(X,Y)\to\mathbb{R}$, $g:(X,Y)\to\mathbb{R}^m$ that are twice continuously differentiable functions. And m is the number of constraints. The number of integer variables is p, and the number of continuous variables is n. *(P)* is an NP-hard combinatorial problem Kannan & Monma (1978). In general, nonconvex integer optimization problems are undecidable Jeroslow (1973). Jeroslow studied a class of integer programming problems under quadratical constraints, and he showed that no existing computing device can compute the optimum for all problems in this class. Yet *(P)* becomes decidable either by ensuring a compact feasible set or by assuming that the problem functions are convex.
There are two fundamental concepts underlying algorithms for solving decidable MINLPs:

- Relaxation
- Constraint enforcement

A relaxation is used to compute a lower bound on the optimal solution of *(P)*. A relaxation is obtained by enlarging the feasible set of the MINLP. The "relaxed problem" of MINLP problem *(P)* is another optimization where a global optimum can be guaranteed and whose solution provides a lower bound on the optimal objective function value of *(P)*. The relaxed problem is formulated as follows:

$$
\begin{aligned}
(R)\qquad & \min \bar{f}(\bar{x},\bar{y}) \\
& \text{s.t.} \\
& \bar{g}(\bar{x},\bar{y}) \le 0 \\
& \bar{x} \in \bar{X} \subseteq \mathbb{Z}^{\bar{p}} \\
& \bar{y} \in \bar{Y} \subseteq \mathbb{R}^{\bar{n}},
\end{aligned}
$$

where $\bar{X} \subseteq X$ and $Y \subseteq \bar{Y}$. Relaxing the integrality of the problem and enforcing lower and upper bounds on variables allow the search for a solution to terminate whenever the lower bound is larger than the current upper bound that can be obtained from any feasible point. Constraint enforcement refers to excluding solutions that are feasible to the relaxation but not to the original MINLP. Constraint enforcement may be accomplished by refining or tightening the relaxation, often by adding valid inequalities, or by branching. We should point out that *(P)* is its own relaxation, i.e. $\bar{f} \le f$. The goal is to find a tight lower bound in the feasible set that is finite-valued, as shown in Figure 1. Based on the Weierstrass theorem, if a closed proper function $f:\mathbb{R}^n\to(-\infty,\infty)$ is coercive, then the set of minima of f over $\mathbb{R}^n$ is nonempty and compact Bertsekas et al. (2003).

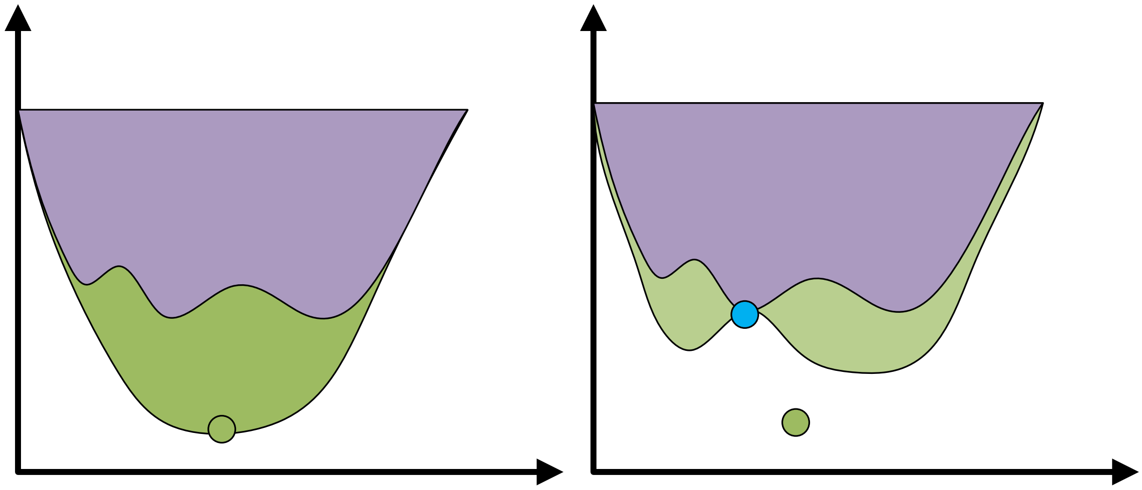

Figure 1. Constraint enforcement for global optimization.

Theorem 1. *If a function* $f: [a, b] \to (-\infty, \infty)$ *is lower semi-continuous,*

$$\liminf_{y \to x} f(y) \geq f(x)$$

for all $x \in [a, b]$, *then* f *is bounded below and attains its infimum.*

3 EMISSION-CONTROLLED MAINTENANCE SCHEDULE FORMULATION

In light of the above theory, we present the problem we considered. The objective, as well as the constraints of the original model, including the relaxed form of the problem, is described as follows. A transportation agency typically utilizes pavement management systems to plan maintenance operations by identifying schedules based on the pavement condition, subject to cost constraints. Current PMSs of the Illinois State Tollway Authority do not typically incorporate environmental considerations into the decision-making process to balance performance and environmental goals. This work seeks to develop a practical and computationally tractable algorithm that would allow the Illinois State Tollway Authority to add an emission-control objective to the current goals—cost and condition of pavement. In this formulation, it is assumed that the agency is operating under a budget constraint, while tracking pavement condition through the IRI and ultimately minimizing greenhouse gas emissions due to maintenance and user activities. The environmental impact calculation from the construction of overlays takes into account both fixed and variable emissions, using results of statistical analysis presented by the Illinois Center for Transportation report on the tollway LCA tool for the Illinois State Toll Highway Authority Al-Qadi et al. (2014). There are two opposing motivations within each section of the objective function. Although an increase in the IRI value causes a linear surge in user emission, scheduling an overlay to lower the IRI value also leads to further emission due to construction activity.

The following forms of IRI progression and drop models were chosen based on work by Al-Qadi et al. (2014). IRI drop model was developed for major rehabilitation activities expected to change the smoothness of the existing pavement surface. Current literature (Wang et al. 2012, Irfan et al. 2008) indicates that the smoothness change of the existing pavement is related to the IRI value before major rehabilitation.

IRI Progression Model

$$IRI_{t+1} = IRI_t + a * d_t^b * ESAL_t^c \tag{3.1}$$

IRI Drop Model

$$IRI_{t+1} = IRI_t - X_{t+1}(m * IRI_t + n) \tag{3.2}$$

The MINLP formulation of the problem is presented as follows:

$$\min \sum_{i,t} d(i,t) * q_i * X(i,t) + p_i * X(i,t) + U(i,t) \tag{3.3}$$

such that

$$IRI_{t+1} = IRI_t + \sum_i a_i * d(i,t)^b * ESAL_t^c * X(i,t) + \left[\sum_i m_i * \left(a_i * d(i,t)^b * ESAL_t^c * X(i,t)\right) + n_i\right] * X(i,t+1) \quad \forall t$$

$$\sum_{i,t} v_i * d(i,t) * X(i,t) + w_i * X(i,t) \leq B$$

$$\sum_i X(i,t) = 1 \quad \forall t$$

$$X(JPCP20, t+1) \leq X(JPCP20, t) \quad \forall t$$

$$X(HMA, t+1) \leq X(HMA, t) + X\left(HMA_{overlay}, t\right) \quad \forall t$$

$$X(SMA, t+1) \leq X(SMA, t) + X\left(SMA_{overlay}, t\right) \quad \forall t$$

$$d(HMA, t+1) * X(HMA, t+1) \geq \varepsilon - L * Y(HMA, t+1) \quad \forall t$$

$$d(HMA, t) * X(HMA, t) + d\left(HMA_{overlay}, t\right)\left(HMA_{overlay}, t\right) \leq M * (1 - Y(HMA, t+1)) \quad \forall t$$

$$d(SMA, t+1) * X(SMA, t+1) \geq \varepsilon - L * Y(SMA, t+1) \quad \forall t$$

$$d(SMA, t) * X(SMA, t) + d\left(SMA_{overlay}, t\right)\left(SMA_{overlay}, t\right) \leq M * (1 - Y(SMA, t+1)) \quad \forall t$$

$$d(JPCP20, 1) = d_0$$

$$d(i,t) \leq u * X(i,t) \quad \forall i, t$$

$$d(i,t) \geq l * X(i,t) \quad \forall i, t$$

where

a_i, b, c : Coefficients of the IRI progression model based on pavement/overlay type

m_i, n_i : Coefficients of the IRI drop model based on type of maintenance activity

q_i: Variable emission proportional to thickness of pavement/overlay

p_i: Fixed emission due to maintenance activity

v_i: Variable cost proportional to thickness of pavement/overlay

w_i: Fixed cost due to maintenance activity

B: Total budget over lifetime of pavement

$U(i,t)$: User phase emission

$U(i,t) = \text{f (IRI, traffic, speed)}$

$M(i,t)$: Emission due to maintenance activity

$M(i,t) = d(i,t) * q_i * X(i,t) + p_i * X(i,t)$

IRI_t: International roughness index value at year, t

$X \in \{0,1\}$: Binary decision variable for state, i of pavement at year, t

$Y \in \{0,1\}$: Binary decision variable for conditional constraint of state, i of pavement at year, t

$d \in \mathbb{R}$: Thickness of pavement or overlay which is bounded as $l \leq d \leq u$.

d_0 : Original thickness of JCPC20

$i \in I$: State of pavement section

I = (JCPC20, HMA, SMA, HMA-overlay, SMA-overlay)

$t \in T$: Planning horizon

M : A sufficiently large upper bound

L : A sufficiently small lower bound

ε : Tolerance value

$ESAL$: Equivalent Single Axle Load for each time period, t

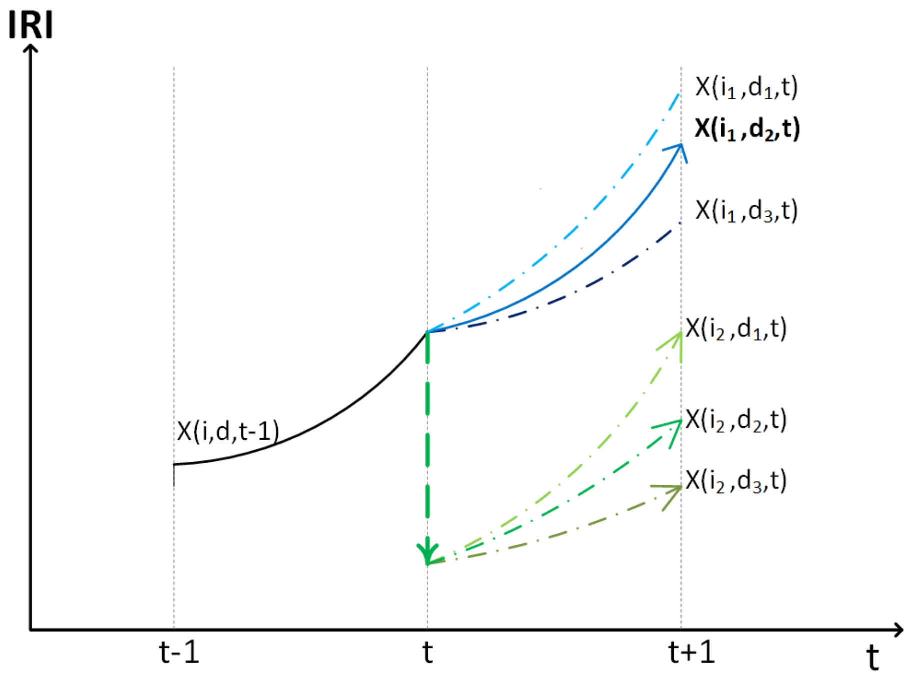

Figure 2. International roughness index vs. decision variable $X(i, d, t)$.

For model 3.3, three levels of decisions are defined: the schedule of maintenance activity, the state of the pavement, and the depth of the pavement/overlay. For time interval $t \in T$, pavement section jointed plain concrete pavement 20 ft. wide (JPCP20) can be in five separate states, which is indicated as a binary decision variable, $X(i, t)$, $i \in I$ such that I = {JPCP2020, HMA-overlay, SMA-overlay, HMA, SMA}. JPCP20 stands for original state of the pavement that cannot be recovered once an overlay is constructed over it. The majority of the JPCP20 original depth within the network is 12 in. The overlay types are hot mix asphalt (HMA) and stone mastic asphalt

(SMA). Pavement can also be in the state of either HMA or SMA where the overlay decision has already been made in previous time periods.

To model the 50 year lifetime of the pavement, our model starts from $t = 0$, $IRI_0 = 60$ that is the roughness index value for a brand new pavement. And also, we define an upper bound for the IRI value that acts as a threshold level. But it is also possible to initialize the model from a random IRI value at a random point in time *t* within the planning horizon *T*. The Monte Carlo approach that we used, which is explained in section 3.1, allows initialization parameter variation of IRI and forecasted traffic volume. The original pavement JPCP20 starts with the initial construction pavement thickness and continues to serve until it is replaced with one of the overlays, HMA-overlay or SMA-overlay. Although switching between overlay types is allowed, recovering to JPCP20 is not possible. Once an overlay decision; HMA-overlay or SMA-overlay, has been implemented at time period *t*, the decision set for the following time period is restricted either to staying at the current overlay or switching to the other overlay type. The depth of the pavement/overlay for time period *t*, *d*(*i*,*t*) is a continuous decision variable with upper and lower bound values. The schedule of maintenance activity decision is embedded into the binary decision variable of *X*(*i*,*t*). Once an overlay decision, HMA or SMA, has been made at time period *t*, and if keeping the aforementioned overlay has been decided for $\{t, t+1, t+2, \ldots\}$, then the depth of the pavement stays the same for $\{d_t, d_{t+1}, d_{t+2}, \ldots\}$ until the next overlay decision is made. Also, the original depth of JCPC20, d_0 stays same until the first overlay decision is made.

The objective function of model 3.3 consists of $M(i,t)$ and $U(i,t)$ environmental impacts of variable and fixed emission due to maintenance activities in time period t and use of the roadway in time period t over the planning horizon for pavement/overlay i. The objective value is given in terms of tons of GHGs (greenhouse gases) per lane-mile. The environmental impacts for construction and use are calculated by considering all upstream and downstream materials and fuel consumption for construction and all upstream and downstream fuel usage from vehicles traversing the pavement for the use phase. An estimate of energy and emissions with respect to a reference speed and IRI values for use-phase framework for pavement LCAs is presented by Al-Qadi et al. (2014). The environmental impact for the use phase considers the additional fuel vehicles traversing the road consume due to additional road roughness. In this study, a model developed by Shakiba et al. (2016) is applied to consider the relationship between extra energy consumption and IRI, assuming an average vehicle distribution found on the Illinois Tollway.

The model uses the international roughness index as the performance criterion. The parameters m and n in equation 3.1 are related to the drop in IRI that occurs with a new HMA or SMA overlay. And the parameters a, b and c in equation 3.2 are associated with the thickness of the overlay or pavement and the equivalent single-axle load (ESAL) or traffic levels at time t. Thus, without intervention, the roughness, IRI_t of the pavement deteriorates following a convex accelerating trend, depending on the existing overlay thickness d_t, pavement/overlay type, and traffic level in terms of million $ESAL_t$. With intervention, the roughness, IRI_t is assumed to drop. If an overlay decision has not been made for the planning period, then increasing the IRI value leads to higher user-emission values. By contrast, if an overlay decision has been made, then the IRI value drops, while emission due to maintenance activity is incurred. The interaction between IRI and decision variables , $X(i,t)$ and d_t be seen in Figure 2.

The problem stated in equation in 3.3 requires interaction of the integer and continuous variables that leads to MINLP formulation. Yet for practical purposes, the continuous variable, thickness of overlay $d \in \mathbb{R}$, can be chosen to be a finite discrete set with cardinality *C*. It can also be mounted into the binary variable as $X(i,d,t)$ which only increases the number of states of a pavement/overlay by *C* in a time period, t. For this particular case, we chose a set of three different thickness options that leads to 15 possible states for the overlay/pavement. The next step to transform the problem into a tractable form was relaxing the integrality of the formulation. We used the Branch-And-Reduce Optimization Navigator (BARON) solver within the general algebraic modeling system (GAMS) distribution 24.7.2 to solve the relaxed MINLP of problem 3.1 within acceptable execution time for the planning horizon of *T* = 50 years.

4 MONTE CARLO SIMULATION FOR PROJECTED TRAFFIC GROWTH

Monte Carlo simulation is a method for exploring the sensitivity of a mathematical model that is simulated in a loop by random parameter variation within statistical constraints. The results from the simulation are analyzed to determine the characteristics of the system in statistical terms.

The output measure from a run of the simulation model, where the number of independent runs of the model is n with the same initial conditions and with different streams of continuous uniform $u \sim U(a, b)$ random variates, then the output data $\{x_1, \ldots, x_n\}$ for each random variable can be treated as statistically independent observations of the random variable. When n increases, due to the central limit theorem, the distribution shape of the sample mean approaches a normal distribution, where

$$L \leq \mu \leq U$$

such that the upper and lower confidence limits $[L, U]$ are obtained from $U = \bar{x} + z_{\alpha/2} S_{\bar{x}}$ and $L = \bar{x} - z_{\alpha/2} S_{\bar{x}}$. $Z_{\alpha/2}$ is the value that gives $P(Z > z_{\alpha/2}) = \alpha/2$. The confidence interval on μ becomes $P(L \leq \mu \leq U) = 1 - \alpha$. The standard deviation of x is denoted as s; and the standard error of the mean, as $s_{\bar{x}}$ is obtained by as $s_{\bar{x}} = s/\sqrt{n}$. $x_{\bar{x}}$ is an estimate of the true mean, μ; and s is an estimate of the true standard deviation, σ. Based on the explanation above, we generated an expanded set of streams of annual traffic of $\{A_1, \ldots, A_{50}\}$ with a growing rate $2 \pm \mu$ % that has an accompanying random noise of μ. We ran a relaxed form of problem 3.3 for each path of traffic stream and recorded the optimal solution set. By repeated random sampling, we created an extended set of traffic-growth paths to run the model.

5 RESULTS

Jointed plain concrete pavement at 20-foot spacing (JPCP20) has been in use by the Illinois Tollway Authority. The JPCP20 pavement sections are maintained based on a predetermined maintenance and rehabilitation schedule. Current practice is SMA overlays of 3–4 inches at *t* = 24,36,44 years. Using the model formulation described in section 3, an alternative rehabilitation schedule of *t* = 20±0.172, 37±0.121, 49±1.112 years, 4-in. HMA overlays are recommended, with a 95% confidence interval in terms of minimizing emission while confirming performance and budget requirements. The resulting IRI performance curves is shown in Figure 3.

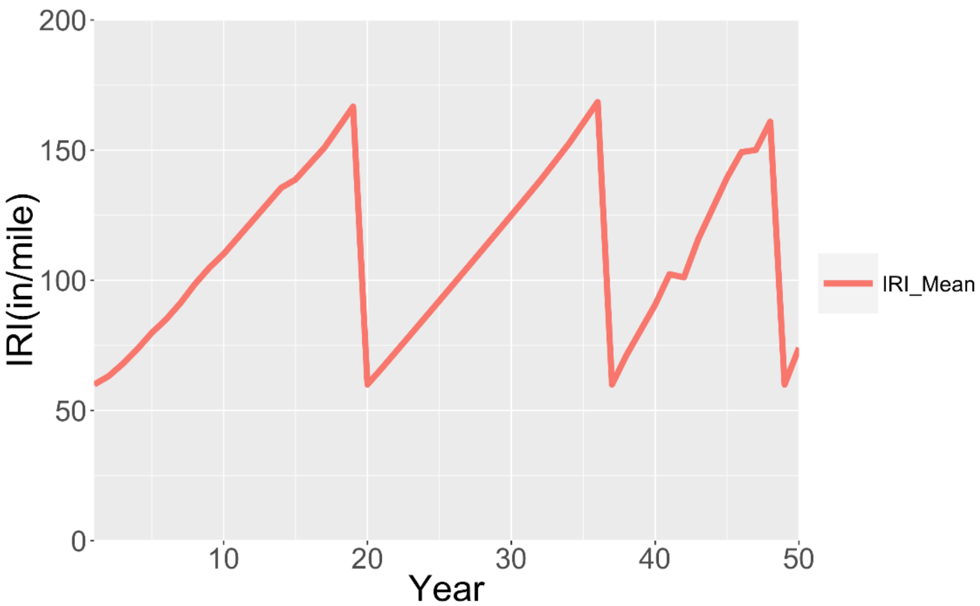

Figure 3. IRI time series as a result of proposed rehabilitation schedule.

Also, using the same streams of annual traffic and the predetermined maintenance and rehabilitation schedule of Illinois Tollway Authority, we calculated the emission over the lifetime of JPCP20; and we observed a 7% reduction in greenhouse gas emission just by changing the set schedule for the pavement rehabilitation and the type of overlay. Also, we point out that the rehabilitation at $t = 49 \pm 1.112$ can be replaced with reconstruction of the existing pavement.

6 CONCLUSIONS

This work is the preliminary step of creating an algorithm that allows agencies to determine the maintenance planning of individual links under budget and emission constraints while complying with performance criterion. We were able to set up an MINLP model of maintenance schedule, overlay type and overlay thickness over lifetime of a JCPC pavement. Although the MINLP model is not tractable, by using relaxation and outer approximation techniques, we were able to solve the problem with a commercial solver. The uncertainty accompanying traffic growth over the planning horizon was also remedied by randomly generating an extensive set of data paths.
As a result of this work we showed that by changing the schedule and type of overlay they currently use Illinois Tollway Authority can lower overall greenhouse gas emission while still staying within economic and performance requirements.

The next scope of this ongoing study is going to be creating a mathematical model for PMSs at network level that takes into account traffic interaction of links as well as user behavior.

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