Network-Wide Life Cycle Cost Analysis That Takes into Account the Effect of Road Roughness on Road Capacity

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ABSTRACT
Life cycle cost analysis (LCCA) is an effective economic-engineering analysis tool to estimate internal and external costs of transportation maintenance projects. LCCA at network level allows decision-makers to find optimum investment strategies with ultimate objective of satisfying network constraints, such as budget or agency resources. This study introduces a new methodology for assessing the benefits and costs of the network-wide LCCA of maintenance projects by utilizing current regional transportation planning models without any additional development and cost customization. One of the main hypotheses of this methodology is the use of the relationship between road roughness and link capacity so that the loss of capacity as a result of the lack of adequate maintenance actions can be used as an input to the regional planning model. This way, it is possible to use well established regional transportation planning models maintained by Metropolitan Planning Organizations (MPOs) to accurately quantify increased network-wide delays. These delays are caused by the reduction in link capacities mainly due to the lack of appropriate maintenance actions. The link capacity is estimated using the fundamental relation of traffic for the speed value, which corresponds to the specific IRI value that is expected to be observed with and without appropriate maintenance decisions. The results show that the benefits related to travel time savings are higher than their maintenance costs for most of the highways. The findings of this study can provide insights in terms of incorporating maintenance strategies that can be developed based on the regional transportation planning models.

Keywords: Life Cycle Cost Analysis, Roughness, Pavement Condition, Benefit/Cost, Road Capacity
INTRODUCTION
In the Life Cycle Cost Analysis (LCCA) perspective, pavement management activities are essential to allocate scarce government resources. An appropriate scheduling of the maintenance operations is necessary to prudently repair and rehabilitate highways. The scheduling of maintenance often depends on some substantial data that reflect highway performance such as the performance index or International Roughness Index (IRI). These values are directly related to the highway safety and service levels. The decline of these performance or roughness values makes drivers more cautious and sometimes it even makes them slow down. Consequently, the speed and other related factors are being affected adversely, and the capacity of the roads is decreased. Additionally, this kind of decrease in capacity leads to an increase in travel time and costs. Thereby taking an action before the capacity loss is essential. To prevent such conditions, pavement management activities must be held. In highway network systems, these management strategies are conducted by using specific prediction models of road surface performances.

Our roadways experience deterioration due to high traffic volumes, harsh environments, and aging. To clarify the maintenance and rehabilitation concepts, the following terms, explained clearly by the Federal Highway Administration (FHWA) (1; 2), are briefly presented. Pavement preservation is a proactive approach to maintain the existing highway systems. FHWA Pavement Preservation Expert Task Group defines it as “a long-term, network-level strategy to enhance pavement performance by using a set of integrated cost-effective practices that leads to extend of pavement life, develop safety concerns and meet the motorist expectations” (1). A successful pavement preservation approach takes precautions before the severe damages of pavements. This approach enables state transportation agencies to reduce the rehabilitation and reconstruction costs and associated traffic interruptions. With this preplanned preservation, it is possible to have longer existing and smoother pavements, decreased congestion, improved mobility, and reduced safety concerns.

Pavement preservation can be categorized into three components: minor rehabilitation, preventive maintenance, and routine maintenance (1). Preventive maintenance is named as a strategy that is scheduled to maintain the asset conditions at desirable levels. This treatment is implied for the extension of average service life. Routine maintenance is a set of maintenance projects that are planned for both protecting the existing highway infrastructure and responding to the specific events. Therefore, this type of maintenance restores the system to a predefined level of service (1). Another concept in this literature is pavement rehabilitation. It can be expressed as structural improvements of the existing pavements to extend their service life and increase their load-carrying capacities (1). Major rehabilitations are pertinent to structural enhancements, however, minor rehabilitations are non-structural enhancements performed onto the existing pavement sections to mitigate the age-related, top-down surface cracks, and environmental effects (1).

Pavement roughness affects vehicle operations, safety, and comfort levels. Roughness also causes wear and tear, hence, it has an appreciable impact on vehicle operating costs (VOC). Improper and delayed maintenance of roads will also result in speed reduction and road capacity while causing an increase in travel time and user costs. To overcome this chronic problem, FHWA has developed highway management systems, such as maintenance management system (MMC) (3).

“Since roughness is often used with other metrics to characterize the health of a road network as a whole as well as to prioritize road segments for maintenance and reconstruction” (4), it is frequently tied to agency’s road maintenance and rehabilitation budget as well. The LCCA, as one of the most widely used economic evaluation tools, is a practical yet highly useful approach
for selecting appropriate construction and maintenance techniques (5). It gives decision-makers the ability to optimize maintenance schedules and allocate required funds based on the actual needs or based on the agency’s priorities if they have a limited budget.

In the LCCA perspective, several pavement management studies are performed on a project-level basis. It is usually not easy to perform a network-level LCCA analysis as it often requires connection to a database, relatively higher computational power and commercial software. In this study, we aim to develop a novel LCCA methodology based on the use of existing regional transportation planning models as the primary source of information for the network-wide evaluation of LCCA for maintenance and rehabilitation projects. In order to quantify the effects of roadway maintenance and rehabilitation, the relationship between speed, pavement roughness, and road capacity is employed. In other words, the vehicle speed is considered as a vehicle movement effectiveness indicator in terms of comfort and convenience (6). Next, by using the Greenshield’s Theorem, International Roughness Index (IRI) is correlated to the speed and capacity of network links. The main idea is first to indirectly model link capacity reductions using the well-established relationship between IRI and speed. Then, using these new reduced link capacities in the regional planning model to quantify increased network-wide delays. The link capacity reductions are experienced as a result of the lack of appropriate maintenance and repair. The utilization of the existing regional planning model requires no additional cost imposed on transportation agencies.

**LITERATURE REVIEW**

Road roughness represents the unevenness of a road surface and is the most significant pavement condition used in the estimation of road-user costs, particularly vehicle operating cost (7). Various methods have been used in the past. Before 1990, Present Serviceability Rate (PSR) and Present Serviceability Index (PSI) on a scale of 0-5 have been mainly used. Since 1990, FHWA accepted IRI value that is useful for relating a roughness measure to ride quality. IRI method assumes roughness as a function of initial roughness level, traffic loading in terms of equivalent standard axle load (ESALs), and age. Other minor factors include pavement thickness, temperature, humidity, and so on. Nowadays, IRI is widely used throughout the world as a measure of road roughness (8).

Some of the models have been developed in the past to study the relationship between pavement parameters and roughness (9-11). The conversion of PSR performance index values to IRI can be done by the formula as below:

$$PSR = 5e^{(-0.0026 \times IRI)}$$  \tag{1}

Research efforts have been conducted to explore the correlation between road roughness and vehicle speed as well. For example, in a study conducted in Australia (12), the effect of road roughness on traffic speed and road safety in investigated in Southern Queensland. The 143 roads data in Australia which the majority of the region has 10% poor roughness used in the model. Data include speed, roughness, crashes, AADT, sealed traffic lane width, general road geometry (i.e., vertical crests, floodways or horizontal curves), the general type of traffic using the roadway (%HV, Road train route, etc.), location of intersections information. The models collectively indicated a strong relationship between higher crash rates and increased pavement roughness. Crash rates involving light vehicles were more affected by increasing roughness than crashes involving heavy freight vehicles. Regarding driver speed, there is 100% driver compliance on segments with roughness over 120 counts/km NRM (4.6m/km IRI), with the 85th percentile speed ranging from 5-15km/hour below the posted speed (12).

Furthermore, the relationship between driver speed and road roughness level has been investigated in (13) by means of the VERA Dynamic Driving Simulator (DDS) (a real car fixed on 6 degrees of freedom motion platform) currently operating at the TEST (Technology Environment Safety
Transport) Laboratory in Naples. The relationship between road roughness and speed has been analyzed using a repeated measures Analysis of Variance (ANOVA) with IRI level following the Mauchly’s test for sphericity that yielded positive results. As a result, the change in the speed was not significant for lower IRI values. A clear dependence of the relative speed-choice on the downward and upward IRI value can be detected. The authors claim that this model represents the unique roughness contribution on driver behavior within a more complex probabilistic speed prediction model taking into account speed constraints related to the road roughness, the desired speed, the driving power, the braking power and the road curvature by means of a harmonic mean (13).

In another study of roughness index and speed relationship (14), using SmartRoadSense, which is a project that aimed at monitoring the surface of road conditions. By using smartphone sensors, the vertical accelerations can be extracted while traveling in a car. These data contain the roughness index information about the road conditions. In Alessandroni et. al. (14) study, 5,800,000 samples of roughness indexes extracted by 1,750,000,000 values of accelerations, obtained from 432 different vehicles using 147 different models of mobile devices. By using the Gaussian model of the road surface, and the quarter-car model of suspension, the power of vertical acceleration \( P(v) \) sensed in a vehicle moving with constant horizontal speed can be estimated. As a consequence, authors indicate that the sensed power of the vertical acceleration and the roughness index of SmartRoadSense depend on the vehicle speed (14).

Table 1 summarizes some of the studies about speed and road surface performance in the literature and data used.

<table>
<thead>
<tr>
<th>Study</th>
<th>Year</th>
<th>Data year</th>
<th>Location</th>
<th>Estimation Method</th>
<th>Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yu &amp; Lu (15)</td>
<td>2014</td>
<td>Between 2000 and 2008</td>
<td>California highways</td>
<td>Regression with a fixed random model</td>
<td>Speed, IRI, Volume to Capacity Ratio, Lane Dummies</td>
</tr>
<tr>
<td>Wang, Harvey, Lea, Kim (16)</td>
<td>2013</td>
<td>Between 2000 and 2011</td>
<td>California highways</td>
<td>Regression model</td>
<td>Speed, Nbr of Lanes, Lane, Caltrans District, Day of Week, Gas Price, IRI</td>
</tr>
<tr>
<td>Karan et al..Model (17)</td>
<td>1976</td>
<td>1974</td>
<td>Ontario, Canada</td>
<td>Regression model</td>
<td>Speed, Road comfort index, IRI, Volume to Capacity Ratio, Speed Limit</td>
</tr>
<tr>
<td>Elkins and Semrau (18)</td>
<td>1988</td>
<td>United States</td>
<td></td>
<td>Exponential model</td>
<td>Speed, IRI</td>
</tr>
<tr>
<td>King (12)</td>
<td>2014</td>
<td>2013</td>
<td>Australia</td>
<td>Linear Model</td>
<td>Speed, roughness, crashes, AADT, sealed traffic lane width (m), general road geometry (i.e. vertical crests, floodways or horizontal curves), the general type of traffic using the roadway (%HV, Road train route etc.), location of intersections.</td>
</tr>
</tbody>
</table>
Four of the studies above are illustrated by numerical examples. These models are listed in the table below:

Table 2. Summary of Roughness to Speed Computation Models

<table>
<thead>
<tr>
<th>Model</th>
<th>Model Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yu&amp;Lu (2014) (15)</td>
<td>Speed = 72.18-0.0083IRI-3.035VCR-3.78L3-2.29L4</td>
</tr>
<tr>
<td>Wang et al (2014) (16)</td>
<td>FFS = a + b x NbrOfLanes + c x Lane + d x CaltransDistrict + e x DayOfWeek + f x GasPrice + g x IRI</td>
</tr>
<tr>
<td>Karan et al. Model (1976) (17)</td>
<td>Speed = 30.7368 + 1.0375RCI – 11.242VCR + 0.0062SPLIMIT [ RCI = 54 – 9.984 \times \log IRI ]</td>
</tr>
<tr>
<td>Elkins et al Model (1988) (18)</td>
<td>VROUGH(AUTOMOBILE) = 1/[0.0250-0.00275(PSR)] [ VROUGH(TRUCK) = 0.9/[0.0250-0.0033(PSR)] ]</td>
</tr>
<tr>
<td>Pernetti, D’apuzzo, Galante (2016) (13)</td>
<td>Speed = 128.6181 – 1.36904IRI²</td>
</tr>
</tbody>
</table>

FFS=Free Flow Speed, IRI=International Roughness Index, VCR=Volume/Capacity Ratio, L3 & L4= 3 and 4 lane dummies, NbrOfLanes=Total Number of Lanes, Lane=Lane Number, CaltransDistrict=District Dummy, DayOfWeek=Day of the week, GasPrice= Gasoline price in dollars, SPLIMIT= Speed Limit, VROUGH=Ride severity speed, PSR=Percent Serviceability Rating, RCI=Road comfort index
The North Jersey Regional Transportation Model Enhanced (NJRTM-E) model (21) is used to evaluate the effect of road roughness on vehicle speeds and road capacities. NJRTME is a planning model that consists of 40 counties encompassing areas from six Metropolitan Planning Organization (MPO’s) or planning areas in New Jersey, New York, and Pennsylvania and Connecticut. Those regional planning organizations are North Jersey Transportation Planning Agency (NJTPA), South Jersey Transportation Planning Organization (SJTPO), New York Metropolitan Transportation Council (NYMTC), Delaware Valley Regional Planning Commission (DVRPC), Northeastern Pennsylvania Alliance (NEPA) and Lehigh Valley Planning Commission (LVPC) (21). The model generates an output containing assigned link traffic volumes for the major highways in the state of New Jersey. Based on the model output, road roughness, pavement surface condition, riding quality, traffic speed, and capacity are then calculated.

**METHODOLOGY**

To measure the damage of pavement in terms of road roughness, Lee’s model (10) is used. This model calculates the PSR and converts it into the IRI. The PSR and IRI calculations have been carried out for different pavement ages of 1, 5, 10, 15 and 20 years using the information provided in the Long Term Pavement Performance (LTPP) (22) program on pavement age selection. Pavement roughness measured in the IRI has been modeled by choosing important and significant pavement variables such as initial roughness value, ESALs, the age of pavement and Structural Number (SN).

Vehicle speed was estimated by the Elkins and Semrau (18). The capacity of pavement sections was computed by using the speed-volume relationships developed in Highway Capacity Manual 2000 (23). From speed-volume relationships, the effect of roughness on road capacity was evaluated. The roadway maintenance cost was then calculated using a cost function developed by Ozbay et al. (24). A cost-benefit analysis has been carried out to obtain cost associated with travel delay and evaluate the importance of roadway maintenance. A stochastic treatment was performed on discount rates, the value of time, and maintenance costs to estimate the variation in the cost-benefit results. The methodology flowchart is shown in Figure 1.
Advanced Software for the State-wide Integrated Sustainable Transportation System Monitoring and Evaluation (ASSIST-ME) (25) developed by the research team is used as the post-processor to visualize and analyze the output of the NJRTM-E model in a geographic information system (GIS) environment. ASSIST-ME can be adopted to any traditional transportation planning model and is designed as a tool to work with model outputs. It incorporates data visualization, data analysis, and output reporting functionalities in a single user-friendly setting, which requires minimal training or knowledge of the models themselves (25). The workflow of ASSIST-ME is shown in Figure 2.
An essential element in pavement design is estimating the ESALs. An estimation of ESAL usually requires traffic counts, heavy vehicles percentage, traffic growth rate, and load equivalency factor. Using the traffic volumes obtained from the NJTPA database, ESALs for each pavement section are calculated using the equation below (26).

\[
ESAL = ADT \times \%TT \times DDF \times LDF \times TF \times 365 \times Y \times G
\]

where,

- ADT=Initial Average Daily Traffic,
- TT=Percent Trucks (decimal),
- DDF=Directional Distribution Factor (decimal),
- LDF = Lane Distribution Factor (decimal),
- TF=Truck Factor (decimal),
- Y=Design Period,
In this analysis, the average daily traffic (ADT) and percent trucks have been calculated from the post-processed NJRTM-E model outputs by using the ASSIST-ME tool. The truck factor is assumed to be 0.39 for the freeway, 0.21 for principal arterial, and 0.07 for minor arterial and 0.23 for other freeways (24). Several growth factors are used for various design periods depending on the assumption of a 2% growth rate. The directional distribution factor (DDF) that accounts for the distribution of loads by roadway direction is assumed to be 0.5 (26). After that, a lane distribution factor is determined from the AASHTO depending on the number of lanes (26).

Since one of the key factors contributing to road roughness is pavement age, the selection of proper pavement age is essential for the purpose of maintenance. Several LTPP pavement sections are selected to observe the impact of pavement age on road roughness. One of the FHWA LTPP studies found that the flexible pavement roughness remains relatively constant over the initial life of the pavement in wet-freeze environments. However, after a certain point, it shows a rapid increase. Most of the pavement sections faces an increase in roughness at the age of 10 to 15 years, and a few of them have very high IRI between the ages of 15 to 20 (27).

Using the collected data for each roadway link and assuming the pavement life of 20 years, ESALs at the end 1, 5, 10, 15, 17 and 20 years have been calculated. The calculated ESALs were then used to estimate the road roughness in terms of the PSR using Lee model (10) (equation (3)). The PSR is converted into the IRI by using equation (1).

\[
PSR = PSR_I - AF(a \times STR^b \times AGE^c \times CESAL^d)
\]  

where,

- PSR_I=Initial value of PSR at construction (4.5 used in analysis),
- STR=Existing pavement: structural number for flexible pavements,
- AGE=Age of pavement since construction (years),
- CESAL=Cumulative 18-kip ESALs in the heaviest traffic lane. (Millions),
- AF=Adjustment Factor based on climate,
- a, b, c, & d= coefficients (a=101.155, b=-1.8720, c=0.3499 & d=0.3385) (10).

**IRI to Capacity Loss Relation**

According to the models above, the IRI changes can be directly related to the capacity losses of highways. In Greenshield’s Theorem (28), the speed-density-flow relationship can be explained in the following equation:

\[
q = k_j(u - \frac{u^2}{u_f}) 
\]  

Where \( q \) is the traffic flow, \( k_j \) is the jam density, \( u \) is the speed, \( u_f \) is the free-flow speed.

The free-flow speed can be related to capacity value, as shown below:
At maximum flow, the value of the speed is half of the free-flow speed. Then, the formula can be written as follows:

\[ q_m = k_j \left( \frac{u_f}{2} - \frac{u_f^2}{4} \right) \]

and then, \[ q_m = k_j \left( \frac{u_f}{4} \right) \] (6)

The capacity-speed relationship in Equation (5) can be incorporated into the IRI vs. Speed models explained in the literature review part. Specifically, Wang et al. (16), Yu & Lu (15), Karan et al. (17) and Elkins and Semrau (18) models given in Table 2 are scrutinized in terms of the capacity change relation directly related to the IRI (or Roughness Level) change of the pavement surfaces. Among these models, it is observed that Elkins and Semrau’s model is much more sensitive than the other models. Elkins and Semrau’s model is selected for this study since it shows the sharpest changes in the capacity values. The model is converted into the modified capacity-IRI equation, and the results are used in the NJRTM-E model for three different case scenarios. Each of these scenarios is explained in the results section. Using \( V_{rough} \) from Elkins and Semrau’s model shown in Table 2 to replace \( u_f \) in Greenshields’s model, the new equation becomes:

\[ q_m = \left( \frac{1}{0.1 - 0.055 e^{(-0.0026 IRI)}} \right) k_j \] (7)

where \( q_m \) is optimal flow capacity, and \( k_j \) is the jam density.

For a numerical example of Elkins and Semrau (18) model, on a freeway, in accordance with the initial IRI value, the 79.02 mph free-flow speed and 8200 veh/hour capacity values are assumed. After the computations \( k_j \) is decided as 414.1 veh/mi. The tabulated capacity values and the comparison graph can be shown as:

<table>
<thead>
<tr>
<th>IRI (in/mi)</th>
<th>Capacity (veh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40.52</td>
<td>8200.00</td>
</tr>
<tr>
<td>60.00</td>
<td>7821.44</td>
</tr>
<tr>
<td>80.00</td>
<td>7484.37</td>
</tr>
<tr>
<td>100.00</td>
<td>7190.21</td>
</tr>
<tr>
<td>120.00</td>
<td>6931.59</td>
</tr>
<tr>
<td>140.00</td>
<td>6702.71</td>
</tr>
<tr>
<td>170.00</td>
<td>6405.38</td>
</tr>
</tbody>
</table>

The results in the table show that the decrease in the pavement condition until the lower limit of the acceptable IRI condition (170 in/mi) indicates the capacity decrease of a given link is around 20%. Therefore, the capacity decrease in capacity level is taken 20% as an approximate estimation for the last case scenario. For the sake of simplicity, we assumed that the capacity of all roadway links will be reduced by 20% which reflects the worst-case conditions.
**LIFE CYCLE COST ANALYSIS**

Maintenance and rehabilitation can be used to restore the pavement performance, which provide a step increase in the pavement condition (29). The schedule of maintenance and rehabilitation actions have a significant impact on the overall pavement life and life-cycle cost of the transportation facility. Thus, decisions about these activities require a proper economic analysis to ensure the best utilization of available funds. The LCCA is performed by computing the discounted monetary equivalency of all benefits and costs associated with each alternative (30). It is the most renowned economic evaluation tool for transportation infrastructure management and decision-making support. Figure 3 explains that the proper timing of rehabilitation is cost-efficient. The total life cycle cost will be less if the pavement is treated on time before it turns into poor condition. For example, it can cost 4 to 5 times as much if the pavement is not maintained after 2-3 years beyond its optimum rehabilitation timing to restore a predetermined pavement condition level (31).

![Figure 3. Demonstration of LCCA (32)](image)

The increase in travel time due to increased roughness have a cost associated with it, which is known as travel time cost. It is one of the non-vehicle operating costs. High levels of pavement roughness may prevent vehicles from driving at the posted speed limit and consequently affects travel time. The resulting increase in travel time can be quantified and incorporated into the proposed LCCA methodology. Since this cost is associated with time, the value of time is a crucial aspect of this LCCA study (24).

As one of the LCCA economic indicators, benefit-cost (B/C) ratio is used to calculate the effect of increased travel time and the monetary value associated with it as well as the maintenance cost of the roadway in this study. The total travel time cost occurred due to a decrease in capacity can be calculated by the following equation. Annual travel time cost has been obtained by multiplying daily travel time cost to 250 working days.

\[ S = \sum_{i} V_i \times TT(V_i, d) \times VOT_i \]  

Where,

- \( S \) = Travel time cost
- \( V_i \) = Volume in veh/hr for vehicle type \( i \)
- \( TT \) = Increase in travel time in hours,
- \( d \) = distance between origin and destination
Two maintenance strategies that are widely used in the LCCA are rehabilitation and reconstruction. For example, the typical rehabilitation strategy used in New Jersey is milling to a depth of 4 in. and overlaying with 4 in. of new asphalt material. For 4-in. milling and overlay, it is reasonable to assume that after the initial overlay successive overlays will be placed and the service life of each overlay is equal to half of the service life for new pavements; while for full reconstruction the service life of each reconstruction is the same as the service life for the initial construction. In this simple example, we use a rehabilitation similar to the one described above. It is assumed that the pavement is newly constructed. Let’s take a reference link as an example, the initial capacity is 2279 veh/hr/ln and the final capacity after 20 years is 2113 veh/hr/ln. The decrease in capacity is assumed to be 7.29%. Simulation results from the regional planning model show that the daily increase in travel time is 5.47 minutes which results in a daily travel time cost of 0.0184 million dollars and an annual travel time cost of 4.61 million dollars. The travel time cost can be saved as a significant benefit if timely maintenance strategies will be applied.

Total maintenance cost is calculated using resurfacing cost function developed by Ozbay et al. (24) using NJ specific data and which is given by the following equation.

\[ C_M = \frac{796.32(M)^{0.40}(L)^{0.39}}{P} \]  

Where,
- \( C_M \) = Cost of maintenance per lane width (1000$/year),
- \( M \) = Road Length (miles),
- \( L \) = Number of lanes,
- \( P \) = Design cycle period

Using deterministic values for the input parameters results in point estimates that may provide misleading suggestions to decision makers (33). Therefore, a probabilistic approach is more suitable to be used in this study. Monte Carlo simulation is performed to treat two input parameters that have high uncertainties probabilistically: 1) discount rate, 2) value of time. The treatment of future costs is from an economics principle that money has time value (33). Therefore, the discount rate becomes one of the most sensitive parameters in the LCCA. Based on a comprehensive survey that summarized the state-of-practice of the discount rate, we assume a triangular discount rate distribution. The minimum and maximum range of the discount rate is 3% to 5% (33), with a most likely value of 3.5% from Office of Management and Budget (OMB) prediction for 2019 (34) using an analysis period of 20 years.

For the value of time, this study applied the recommended dollar range used by WSDOT in 2010 dollars and converted them into 2019 dollars considering the inflation (35; 36). Triangular distributions are built based on these ranges for different types of vehicles: 1) passenger vehicles: \( \text{VOT}_p \sim \text{triangular} \left(15.1, 17.4, 19.75\right) \), and 2) trucks: \( \text{VOT}_t \sim \text{triangular} \left(25.56, 30.7, 36.01\right) \) (37).

For the benefit/cost analysis, two different scenarios are considered for the 20-year analysis period. In the first two cases, the assumption is to shut down 1) ten different bridges with the highest ADT are shut down due to the unacceptable pavement conditions and, 2) ten random bridge links in New Jersey are chosen to be closed for similar activities. In the third scenario, previously derived IRI to the Capacity function of Elkins and Semrau’s model is considered to evaluate the maximum capacity reduction because Elkins and Semrau’s model gives the sharpest decrease among other models (Yu & Lu (15), Karan et al. (17), Wang (16)). In that case, the decrease to the boundary point of an acceptable IRI (170 in/mi) (38) corresponds to approximately 20% reduction.
of the network capacity. Therefore, in the NJRTM-E model run, the capacity values of all links are decreased by 20% to reflect the worst-case conditions for the overall network pavement condition. The results of the first two scenarios are shown in Table 4.

**Table 4. Results of Scenario 1 and 2**

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Time-Saving</th>
<th>Cost</th>
<th>B/C Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>Mean: $ 29,506,393 St. dev.: $ 1,885,326</td>
<td>$ 17,539,770</td>
<td>Mean: 1.6823 St. dev.: 0.1075</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>Mean: $ 9,569,648 St. dev.: $ 611,457</td>
<td>$ 5,742,005</td>
<td>Mean: 1.6666 St. dev.: 0.1065</td>
</tr>
</tbody>
</table>

The Probability Density Function (PDF) and Cumulative Distribution Function (CDF) for Scenario 1 and Scenario 2 are provided in Figure 4. Table 4 and Figure 4 (a) show that in both scenarios, travel time savings are more significant than the corresponding maintenance costs. However, the travel time savings are more uncertain in scenario 1 compared to the second scenario since it has a wider distribution (higher standard deviation) in terms of its PDF (Figure 4 (a)). Although the savings and costs are different, both scenarios have very similar B/C ratio (Figure 4 (b)). The CDFs of the B/C ratio provides additional information about the risk for different investment strategies. For example, scenario 1 has 74.4% probability that it has a B/C ratio larger than 1.6 (circle point), whereas scenario 2 has 70.0% probability that it has a B/C ratio larger than 1.6 (star point).
The results in the first and second scenarios show that the links with traffic closure have a significant effect on the capacity decrease of the overall network and therefore travel times increase. For each scenario, Benefit/Cost ratios are larger than 1. It shows that when the links are not maintained, and the pavement conditions are lower than acceptable levels, the overall network is adversely affected. Therefore, preventing the links’ pavement conditions fall under acceptable threshold leads to a lower efficiency in the network travel time that can be remedied by employing appropriate maintenance actions that provide cost-effective outcomes based on the favorable B/C ratios obtained from our analysis.

In the third scenario, the overall network maintenance cost is calculated using approximate values rather than focusing on individual and highly detailed link-based analysis conducted using a regional planning model. In this approximate network-wide analysis, the average lane number per link is assumed as 1.37, which is the weighted average of the total links. Each link’s number of lanes is multiplied by the corresponding link length, and then the results are summed up and divided by the total link length. The link length is taken as the average value of the total network length. Instead of using the B/C ratio analysis, an equivalent link number corresponding average cost of maintenance projects is calculated for this scenario. The reason behind this approach is because performing maintenance actions in a single year (in this scenario, we assume at the end of year 20) is far from being a feasible approach and leads to exorbitantly high maintenance costs and
meaningless value of B/C ratio. The results are shown in Table 5 and Figure 5. Benefit in these scenarios is estimated by using the saving of travel time based on VOT. Triangular distributions of VOT for passenger vehicles and trucks are assumed as mentioned in the previous section, and Monte Carlo simulation is performed to generate random samples from the given distributions (5,000 runs).

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Time-Saving (discounted to today’s NPV value)</th>
<th>Corresponding cost of link maintenance number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 3</td>
<td>Mean: $33,040,087 St. dev.: $3,008,976</td>
<td>1,669</td>
</tr>
</tbody>
</table>

Figure 5. Graphs of stochastic analysis for Scenario 3

In the third scenario, the modified Elkins and Semrau’s model is used to compute the capacity reduction due to the IRI change. For the boundary condition of an acceptable IRI value (170 in/mi), corresponding benefits and the costs are estimated. The benefit values for keeping all the highway links at their best level before falling under 20% capacity loss provides much higher values than those in the first two scenarios. In other words, when the overall network capacity falls under 20% of its total capacity, it leads to a much higher travel time decrease than the first two scenarios as expected. The PDF and CDF of the travel time saving are illustrated in Figure 5. After applying the stochastic treatment, the probabilistic output shows that there is a 50% chance that this scenario can save more than 25.8 million dollars and 20% chance that it results in savings more than 28 million dollars if the maintenance actions are taken on time. As an alternative approach to the B/C ratio, the maintenance costs are considered as equal to the benefit values to meet the point where the feasible region is reached, we observe that it is feasible to schedule 1,669 links out of 57,239 links in the network for maintenance actions. In other words, for a 20% decrease in network capacity, results indicate that it is feasible to schedule 1,669 links for maintenance actions for each year. Of course, it is possible to use more advanced search algorithms to select the best 1600 links that will maximize benefits in terms of their impact on the overall network congestion and delays.

DISCUSSION AND CONCLUSIONS
This study presented the research efforts of incorporating well-known transportation planning models into the life cycle cost analysis studies to improve the decision-making process of highway
The main idea is to first indirectly model link capacity reductions using a well-established relationship between the IRI and speed. The reduction in link capacities is mainly due to the lack of appropriate maintenance and repair. Next, we used these reduced link capacities in the regional planning model to quantify increased network-wide delays. In this study, we presented a new LCCA approach for evaluating the economic benefits and costs. The first two case scenarios used a total of 20 pavement sections. The third scenario used all the roadway links in the NJRTM-E regional planning model. After reviewing the literature, the Elkins and Semrau’s model is selected to build the relationship between the capacity and IRI since it reflects the sharpest changes in the capacity values. The propose model is then used in capacity reduction calculations.

Capacity-IRI relationships indicate that road capacity decreases as a result of the increase in road roughness. In the first case scenario, ten busiest bridge links are closed for maintenance and other rehabilitation activities based on the assumption that their pavement conditions are unacceptable. The second case scenario is similar to the first one, but the only difference is the ten bridge links are chosen randomly. The results of the benefit and cost estimations of these two scenarios show that the benefits of travel time savings are more significant than the maintenance costs. Obviously, the benefits of the first case scenario are far larger than the second scenario because they carry much higher traffic volume.

In the third scenario, the overall network capacity is decreased by 20% according to the IRI to Capacity model. The results of this scenario indicate that the benefits cannot compensate for the cost of the overall network maintenance in a year. This is an expected outcome because performing maintenance actions for all the network links in a single year is not a feasible option. When the Benefit/Cost ratios are taken as 1 at different VOT and discount rate assumptions in this scenario, the results show that maintaining about 1,669 links generate feasible results for each year.

The new LCCA approach shows that road rehabilitation in a proper time manner can lead to the direct benefit of travel time savings by avoiding increased IRI and a decrease in road capacity. Maintenance cost has been calculated to obtain B/C ratios. Sensitivity analysis has been carried out for different VOT to observe the variation in B/C ratios. Results obtained in this analysis and previous studies \((39-41)\) on cost-benefit analysis show a similar trend, but assumptions made in each study are different as well as the value of time, ADT of facility and length of the facility are different. Results indicate that at any VOT, benefits are going to be higher for most of the roadway links than the cost of maintenance in the first two scenarios. In the third case scenario, the results indicate that travel time losses in the loss of capacity of the whole network effects much higher levels than the other scenarios of closing only ten bridge links. The overall results indicate that if we maintain roads in a timely manner, this will lead us to the savings associated with travel delay. Consequently, pavements should be maintained at an appropriate schedule to reduce roughness and travel delay and thus ensure effective operations. In the future, optimal selection of links given budget constraints and addition of other external costs such as accidents, noise, and vehicle maintenance will be considered.

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AUTHOR CONTRIBUTION STATEMENT

The authors confirm contribution to the paper as follows: study conception and design: Onur Kalan, Abdullah Kurkcu, Jingqin Gao, Kaan Ozbay, Vacha Desai, Drashti Joshi; data collection: Onur Kalan, Abdullah Kurkcu; analysis and interpretation of results: Onur Kalan, Abdullah Kurkcu, Jingqin Gao; draft manuscript preparation: Onur Kalan, Abdullah Kurkcu, Jingqin Gao and Kaan Ozbay. The author reviewed the results and approved the final version of the manuscript.

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