A REVIEW OF PAVEMENT ECONOMIC STUDIES AT THE MIT CONCRETE SUSTAINABILITY HUB

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ABSTRACT

In 2009, the United States cement and concrete industries established the Concrete Sustainability Hub at the Massachusetts Institute of Technology to develop more sustainable and durable pavement infrastructure and buildings. With respect to pavements, one area of focus has been on improving the economic procedures related to pavement type selection practices at both the project-level and network-level; and creating a better understanding of the impact that those decisions can have on an agency's expenditures and pavement network performance. On the project level, MIT has focused on improving the Life Cycle Cost Analysis (LCCA) process so that the results are more representative of the agency's costs and the user's cost. At the network level, MIT determined that a diversified pavement network (one that uses both concrete and asphalt solutions) performs better for the same total pavement expenditures when compared to a pavement network made up of only one material. The goal of this paper is to summarize the relevant MIT CSHub pavement economic research to date and show how agencies can use this information to improve the efficiency of their roadway and pavement investments.

KEY WORDS

LIFE CYCLE COST ANALYSIS / ASSET MANAGEMENT / PAVEMENT MANAGEMENT / MATERIAL PRICE PROJECTIONS / COMPETITION

1. INTRODUCTION

In 2009, the United States cement and concrete industries established the Concrete Sustainability Hub (CSHub) at the Massachusetts Institute of Technology (MIT) to carry out a multi-year research program to evaluate and improve the environmental and economic impact of concrete in pavements and buildings. The goal of the effort is to develop breakthroughs that will lead to more sustainable and durable pavement infrastructure and buildings by (1) providing a scientific basis for informed decisions; (2) demonstrating the benefits of a life-cycle view; and (3) transferring research into practice.

With respect to pavements, one area of focus has been on improving the economic analysis practices to more accurately reflect the most likely expenditures for each alternative over the analysis period. For example, MIT determined that paving materials (asphalt and concrete) inflate at different rates and by not taking this into account; agencies could inadvertently bias the results and make inefficient choices in their pavement selection. MIT also determined that sustained and viable competition between paving industries can be an opportunity to lower bid prices. The goal of this paper is to summarize the relevant MIT CSHub pavement economic research to date. Key items to be discussed are:

- How accounting for material specific inflation and using future price projections improves a project level LCCA.
- How Pavement Vehicle Interaction (PVI) can be incorporated into user cost calculations.
- How inter industry competition lowers pavement material unit prices.
- How diversification and allocation choices in pavement maintenance and rehabilitation activities improves a pavement network performance

2. HOW TO ACCOUNT FOR MATERIAL SPECIFIC INFLATION IN A PROJECT LEVEL LIFE CYCLE COST ANALYSIS

Life cycle cost analysis is an economic process used to determine the total “costs of ownership” of an asset, such as a pavement, over the analysis period, considering all significant costs expressed in equivalent present value dollars. It is intended to ensure that short term savings at initial construction do not lead to long-term deficits due to higher future maintenance requirements. Most often, it is used to compare different options for a given project to determine which pavement design is most cost effective. However, to be meaningful, credible, and provide the information needed to make the best selection, the economic analysis must reflect the most likely expenditures for each alternative as accurately as possible.

Current LCCA practice for pavements is to assume that the price of all materials grows at the general rate of inflation (referred to as the “no change” model). This means that future costs are predicted to inflate at the same rate as the average for all goods and services in the economy (quantified as the consumer price index – CPI or Producers Price Index – PPI). However, national data from the USA Bureau of Labor Statistics (BLS) on pavement construction material prices (e.g. asphalt paving, cement, ready mix concrete, steel and aggregates) show that asphalt has inflated differently than the general inflation and other materials (Figure 1) (BLS, 2018). This data and other works (Lindsey, Schmalensee, & Sacher, 2011; I. Mirzadeh, 2015; Mack, 2012) demonstrate that the practice of assuming that paving material prices grow at a steady rate tied to general rate of inflation in an LCCA (also known as “no real price change”) is inconsistent with how the historical price of these commodities have actually evolved over time. Ignoring this experience will bias the cost estimates in the LCCA and will potentially lead to costly overruns on both the project and network level.

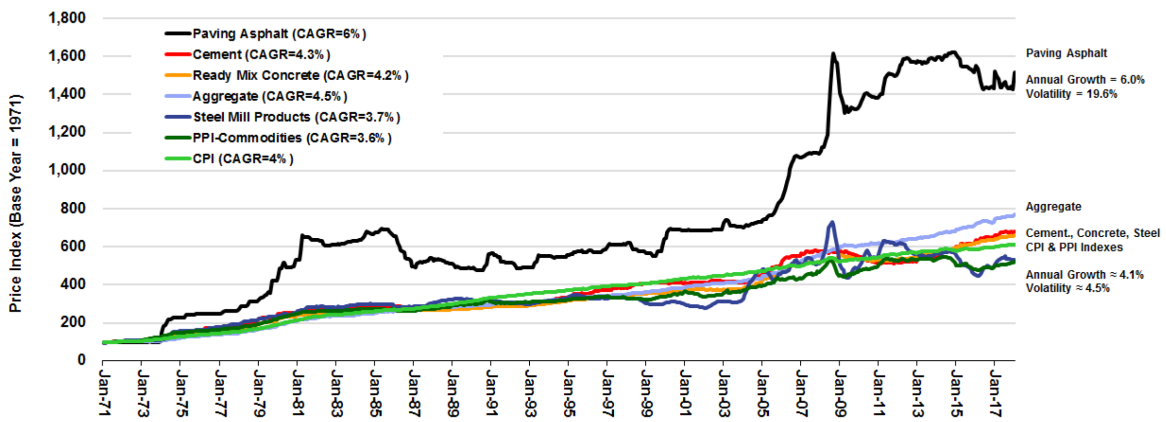


Figure 1 – Comparison of annual inflation rates for pavement construction materials and two indicators of general rates of inflation (PPI and CPI).

The difference between a specific product’s inflation and the general rate of inflation is known as *real price change* [1] and the economic procedure to account for its impacts on future material cost estimates is called *escalation*. Escalation is essentially the difference between inflation of a given product (concrete or asphalt) and the general rate of inflation. The future price of an activity in a LCCA is found by increasing (decreasing) or escalating the current price to the future price by using the following formula:

$$\text{Escalated Price} = \text{Current Price} \times (1+e)^n, \quad (1)$$

[1] Real Price Changes is also known as changes in relative prices, differential Inflation rates, material specific inflation, and constant dollar changes. All mean the difference between a specific material or product’s inflation rate and the general rate of inflation, and these differences can either cause an increase or decrease future prices

where

e = escalation rate

n = year of activity

The reason for correctly accounting for inflation, aka real price changes is that it has the potential to improve future cost estimates by LCCA, thereby improving its reliability and credibility. While the above escalation principal is an easy concept, as stated earlier most pavement LCCA's do not use escalation for the following reasons:

1. The current Federal Highway Administration (FHWA) / Department of Transportation (DOT) guidelines for pavement LCCAs do not specifically require that "real price changes" be accounted for in the developing the cost estimates.
2. There are no "real price forecasting models" for paving materials
3. There is no evidence that escalating future prices using real price changes improves the future cost estimates in LCCAs or is more accurate than using the last known price in perpetuity.

Addressing the first concern is relatively easy. Accounting for real price changes in a LCCA is a valid economic practice recommended, endorsed, and used in many applications. For example, in building LCCAs, the National Institute of Standards and Technology life cycle costing manual for the Federal Energy Management Program and the American Society for Testing and Materials (ASTM) Standard Practice Designation E917-05 both employ the process to adjust energy-related costs based on the projections of real escalation rates (real price changes) for fuel types used in the operation of government buildings (NIST, 1996; ASTM, 2005). Similarly, the Office of Management and Budget (OMB) state in Circular A-94 "Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs" that *"…estimates may reflect expected future changes in relative prices, however, where there is a reasonable basis for estimating such changes"* and reaffirmed this principal in a 2012 Interpretation review. (OMB, 1992; OMB, 2012). Other US Governmental Agencies publications that discuss how accounting for real prices can be done are found in the following references (Army, 1992; Lee & Grant, 1965; FHWA, 2003; GAO, 2009).

Table 1 shows the current FHWA LCCA process, and how it could be adjusted to account for real price changes with minor modifications. The first part of the process establishes the frame work on how the LCCA will be performed. The second part lays out the recommended steps to performing a LCCA. The bullets in red italics are the additional steps needed to account for real price changes.

The focus of the MIT's research has been on items 2 and 3 – developing real price forecasting models" that predict future cost estimates better than the current "no change model" and providing evidence that forecasting future prices using historical real price changes improves the future cost estimate. With respect to this, it is important to recognize that not accounting for potential real price

Table 1: Modifications required to update FHWA's LCCA process to account for real price changes

Establish LCCA Framework	• *Establish analysis period*
	• *Establish how inflation will be treated (nominal or real)*
	    • *Determine if inflation rates are similar to the general rate of inflation*
	    • *If not, develop "escalation rates" as needed*
	• *Establish discount rate to be used (nominal or real)*

Perform LCCA	1. Establish Alternative Pavement Strategies
	2. Determine Rehabilitation Activity Timing
	3. Estimate Agency and User Costs (UC are optional)
	    a. Initial Construction Costs
	    b. Rehabilitation Costs
	        • *Escalate cost to the activity year to account for "Real Price" Changes*
	4. Compute Life-cycle Costs
	5. Analyze the Results

changes is a conscious decision to use a "no change" model that predicts future costs will grow at the general rate of inflation, and will have the same "real price" as today. Though this is easy to do, it is a simplistic assumption and not realistic of how prices have grown.

To develop their real price forecasting models, MIT proposed developing a life cycle cost estimating approach that independently models the expected cost of the materials using a probabilistic approach in order to better understand risk and uncertainty. That is, the majority of forecasting models are deterministic, relying on past behavior or trends to construct a single-point forecast of the future. An example of this is the US Energy Information Agency's Petroleum Market Model that projects a single price point in the future, such as the price of oil in 2030, based on production trends (EIA). While useful, the primary weakness with such a deterministic model's results is that it can fall short due to the lack of accounting for uncertainty and their inability to handle random events such as earthquakes or political instability.

Probabilistic projections also use past behavior to predict the future, but consider the uncertainty within the projections. A probabilistic result may state: in 2030, the price is most likely to go up by 5%, but there is a 10% chance that it could go up by 10% or more and a 10% chance that the price could drop. An example of probabilistic modelling is the National Oceanic and Atmospheric Administration (NOAA) hurricane prediction models. These models use past data on weather conditions to predict a suite of potential hurricane paths that make up the trademark "cone of uncertainty" that forecasts the areas that could be affected by the storm. Such an example is shown in shown Figure 2 for Hurricane Isaac's path (NOAA, n.d.)

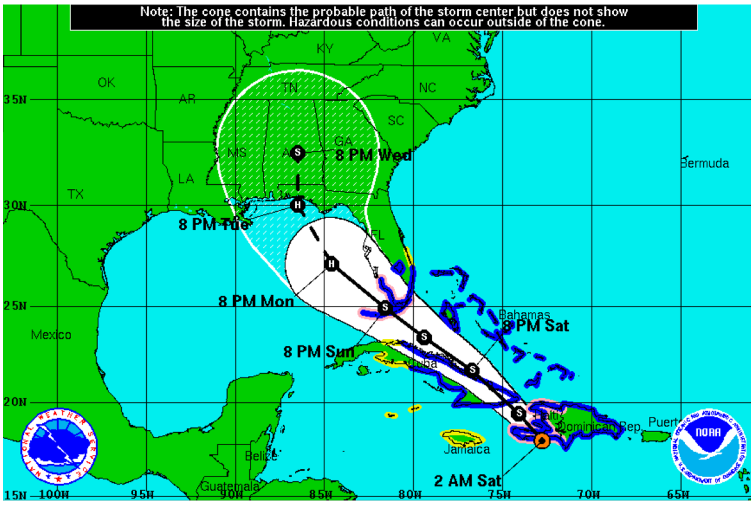


Figure 2: Hurricane Isaac projected path

The MIT CSHub price projection model uses the same probabilistic approach to account for uncertainty and risk in the LCCA cost estimates in the LCCA, which is particularly important when considering the long analysis period of 30-50 years used for most road projects. The MIT price projection also uses the same assumption that most forecasting models follow: past behavior is the best available predictor of future behavior.

However, one of the issues with using historical data for the concrete and asphalt is that that the time frame for which the data has been collected is limited (approximately 30 years) and therefore it may not capture the long term macroeconomic trends of the concrete and asphalt commodities (e.g. the long-term increase / decrease of the material prices due to shocks in the system from items such recessions, oil embargoes, increased construction activities, etc.). Still, because it is monthly BLS commodity data, it is plentiful. On the other hand, there is significant long-term data for the key material inputs, referred to as constituents, that make up concrete and asphalt paving materials dating from the early 1900s. The problem is that while it is significantly long-term data; it is on annual basis and is not as plentiful as the monthly BLS commodity data.

MIT proposed a 2-step approach where they first showed that the paving material commodities and their constituents behaved similarly and had a price trend relationship using the extensive monthly, but short term (30 year) data from the Bureau of Labor Statistics (BLS). As an example, Figure 4 shows how the price of asphalt has tended to follow the composite trend its constituents (sand and gravel, crushed stone and oil). Figure 3 shows the constituents originally considered for concrete and asphalt. Note that not all these constituents are included in the final models.

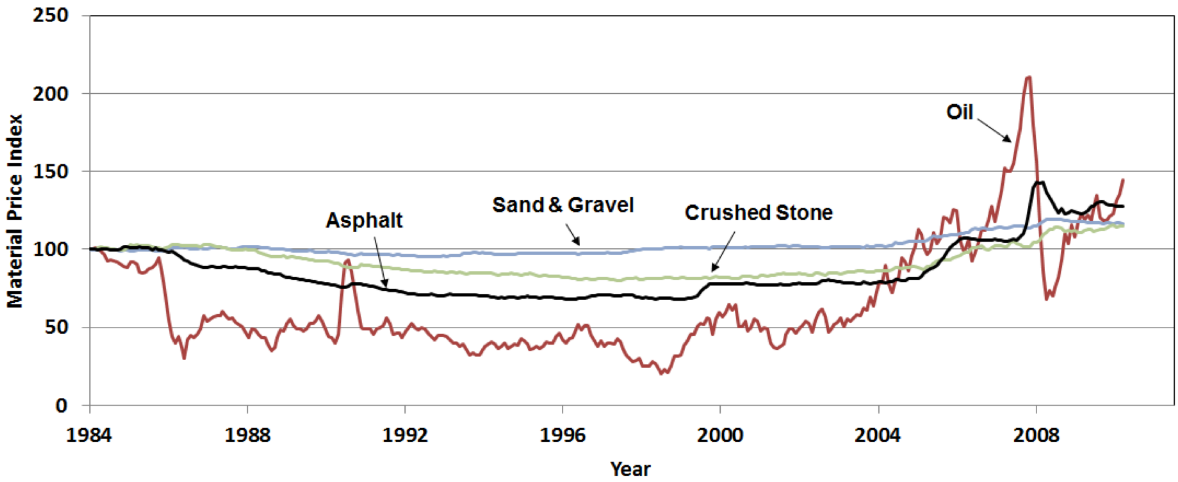


Figure 4: Example of how a commodity price (asphalt) follows the composite trend its constituents and can be used for the basis for price projection models

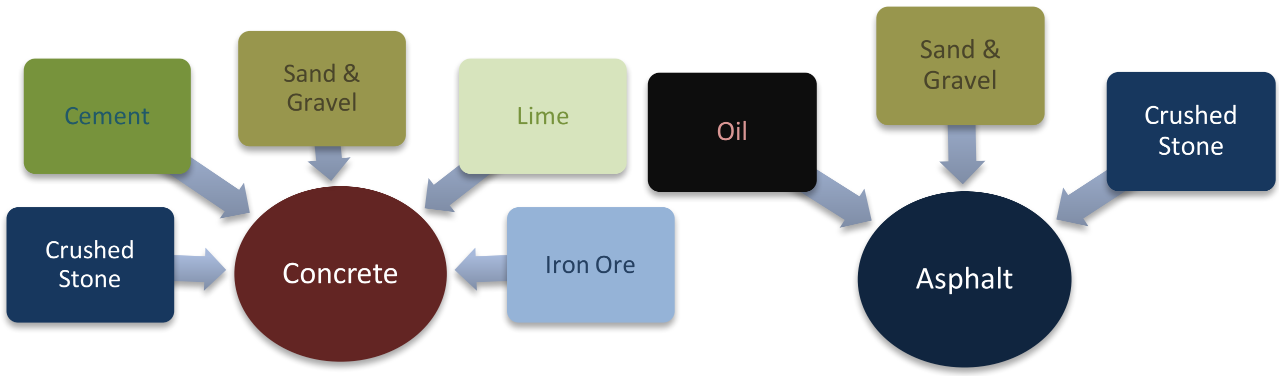


Figure 3: Constituents originally considered for asphalt and concrete price projection models

The second step was then to use that relationship and the annual, long term (100 year) historical constituent data to develop price trend forecast models that captures the long-term macroeconomic trend of the concrete and asphalt materials themselves. This approach of focusing on the key constituents independently to establish a long-term forecast trend model allowed MIT to build a model for forecasting asphalt and concrete prices that greatly improved the quality of the final results. The following four steps highlight the complete process. For details see references (Swei, Gregory, & Kirchain, 2013), (Swei, Gregory, & Kirchain, 2015) and (Swei, Gregory, & Kirchain, 2017).

Step 1: Establish a long-run price trend between asphalt, concrete, and their constituents.
This step used the monthly data from the BLS for ready-mix concrete, asphalt paving, crushed stone, and cement data sets dating back to January 1985 and Brent spot oil prices starting in May 1987 to determine if there is long-run price trend between paving materials and their constituents (BLS, 2015; EIA, 2015). Again, the reason for using monthly data rather than annual data is due to the minimum sample size needed to determine if there is a relationship between the commodities (asphalt or concrete) and their constituents.

The process used to determine if there is a relationship between asphalt / concrete and their constituents is called "cointegration." Items are considered cointegrated if they shift randomly through time but never far apart from one another (Figure 5 shows an example of two materials demonstrating co-integration). Determining cointegration assures that there is not spurious relationship between two unrelated items. One such example is the correlation that shows amount of ice cream sold monthly and correlates with deaths by drownings. It is not that ice cream causes drownings, it's that ice cream sales and swimming both occur during the warm months. Determining cointegration is a detailed process and the reader is again directed to (Swei, Gregory, & Kirchain, 2013; Swei, Gregory, & Kirchain, 2015; Swei, Gregory, & Kirchain, 2017) for additional details.

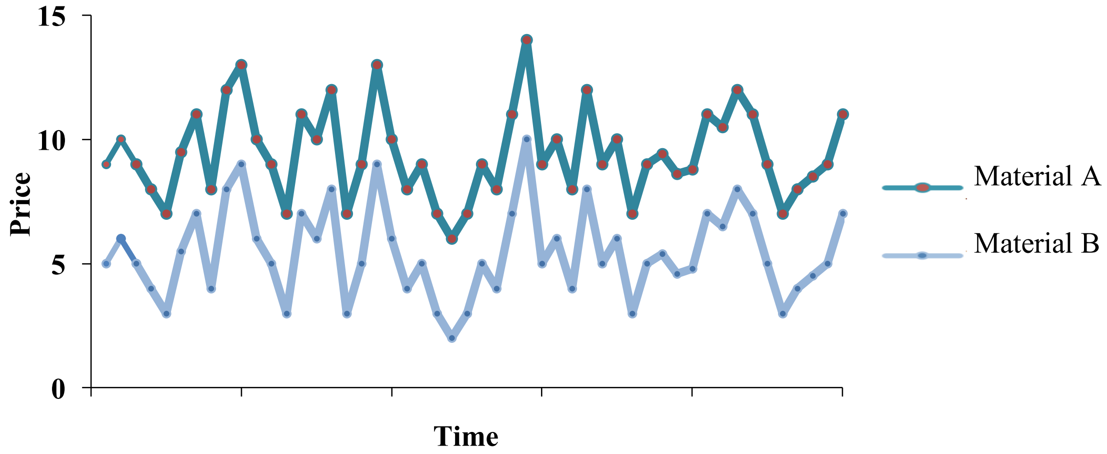


Figure 5 - Example of two materials demonstrating co-integration

MIT has actually performed this analysis two different times – one in 2013 (based on data until 2011) and again recently in 2017 (based on data up to 2013). In the 2013 analysis, MIT determined that price of paving asphalt was cointegrated with sand, crushed stone and oil whereas concrete was cointegrated with the prices for crushed stone and cement. In the 2017 analysis, MIT determined that asphalt was cointegrated only with crushed stone and oil (sand dropped out) while concrete was still cointegrated with crushed stone and cement. Equations 2 and 3 show the relationship from the 2017 evaluation between the asphalt and concrete with their constituents.

$$P_{asphalt;t} = 1.41^*P_{crushed\ stone;t} + 0.20^*P_{oil;t} - 61.6 + N(0;\ 3.5) \quad (2)$$
$$R^2 = 0.96$$

$$P_{concrete;t} = 0.51^*P_{crushed\ stone;t} + 0.44^*P_{cement;t} + 5.3 + N(0;\ 1.6) \quad (3)$$
$$R^2 = 0.95$$

where $P_{x;t}$ = price of commodity x in year t. The last term is a Gaussian distributed random error.

Step Two: Project the future price of pavement constituents and materials.
This step projected the price of pavement constituents found to be cointegrated with asphalt and concrete into the future using a time series model. The constituent price projections used in this step are based on standard, widely used models. A minimum of 50 years of data was used to make the constituent projections. In developing their models, MIT also needed to determine whether the materials exhibited stationary (mean-reverting) characteristics or nonstationary characteristics, such as random walk with a drift term to account for the upward or downward movement of the timeseries.

Based on the data analysis, it was determined that cement follows a slow, yet present, mean-reversion characteristics to a constant mean whereas crushed stone was found to follow a geometric Brownian motion process. Oil was found to be best modeled with simple quadratic mean-reverting process to a continually shifting mean, which accounts for the continually shifting marginal cost of oil production. Equations 4, 5 and 6 shows the Long-Run Price Equilibrium models for each of the constituents from the 2017 analysis:

$$\text{Crushed stone: } P_t = P_{t-1}^*e^{(-0.0045+N(0;0.047))} \quad (4)$$

$$\text{Cement: } P_t = 0.89^*P_{t-1} + 14.3 + N(0;\ 9.5) \quad (5)$$

$$\text{Oil: } Log(P_t) = 65.1 - 0.067^*t + 1.75 \times 10^{-5}\ {}^*t^2 + 0.82^*Log(P_{t-1}) + N(0;\ 0.10) \quad (6)$$

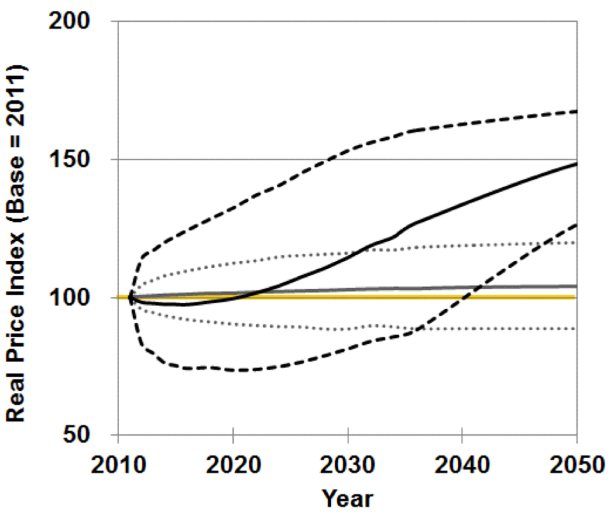
where P_t = price in year t; P_{t-1} = price in year t − 1; and N (μ, σ) = normal distribution with a mean of μ and a standard deviation of σ..

It is important to note that the above oil model leads to an expected increase in real oil prices to twice their 2013 levels by 2025. To account for the model potentially overestimating future costs, a price cap of 2.4 times the 2013 real price of oil is implemented, which is consistent with what the U.S. Energy Information Administration (EIA) considers as its high price scenario by 2040. (Conti, 2015).

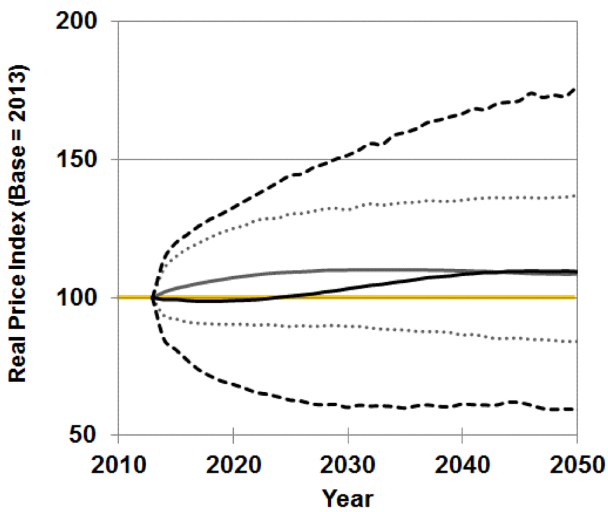
Step Three: Project the Future Price of Paving Materials:
Once the relationships between the commodities and their constituent materials; and the long-run price trend projection models for the constituents were developed, the two sets of models were integrated to make probabilistic forecasts for concrete and asphalt. This was done by performing a Monte Carlo simulation with thousands of predicted concrete and asphalt prices over the next 40 years to estimate the mean, 5th percentile, and 95th percentile projected price in each year. Figure 6 shows the probabilistic real-price projection for concrete (gray lines) and asphalt (black lines) for both the 2013 and 2017 models. The dashed lines represent the 5th/95th percentile of the forecasts, and the solid lines represent the mean expected price.

In comparing the 2013 and 2017 models, there are a couple of things to note. First it can be seen the shape of the mean models changed, especially the asphalt model. That is, in 2013 the asphalt and concrete mean models differed significantly, but by 2017 both models had shifted such that the two mean models no longer showed a large difference in future expected prices. Secondly, it can be see that the expected volatilities between the 2013 and 2017 model widened. That is, both the concrete and asphalt volatility increased, but again, with the asphalt variability increased (became wider) more than the concrete variability. These changes indict why the models should be updated on a regular basis.

Step Four: Validate the Relative Performance of Price Projection Models to Current Practice.
The final step is to determine if the accuracy of the future price projections produces better results than the current "no change model" that is used. To do this, the probabilistic price model / approach described here is developed using a set of commodity data in the past up to a given year (e.g. 1980). Then that model is used to create price projections from that point on and the projection results are compared to the actual data. This process is known as backcasting, and can be used to understand



(a) 2013 Analysis



(b) 2017 Analysis

Figure 6: Probabilistic real-price projection for concrete (gray) and asphalt (black). Dashed lines represent the 5th/95th percentile of the forecasts, and solid lines represent the mean expected price

and quantify the performance of different models as well as to contrast the results with the standard no change models. MIT performed backcasting in a couple of different ways. First, they compared results for each of the individual commodities (asphalt and concrete) on a national basis, and secondly, they performed a more detailed analysis by using it in a LCCA process at a state level. For brevity, only the state analysis will be discussed in this paper.

To evaluate the projection modeling process at a state level, MIT conducted a research project with the Colorado Department of Transportation (CDOT) to among other things, investigate whether projecting paving material prices in CDOT's LCCA process would be an improvement over the existing assumption that future prices grow with inflation (e.g., constant real prices aka the no change model). MIT conducted LCCAs for the projects using CDOT's standard practices and with projected real price changes using the 2013 national material-specific price projection models and scaled to the state level (the 2013 model was used as this research was done in 2014). The CSHub researchers used this approach because national data sets provide more extensive information than state data sets, which may only include a few decades of prices. Researchers looked at how well price projections starting from 1987 would have predicted rehabilitation costs using CDOT's standard current practice (no change in real prices) and MIT's forecasting models.

Figure 7 shows the results of the analysis comparing the two approaches. As can be seen, using material specific projections produced better results than the current no change assumption; which shows that cost projections are a better practice and they do improve the accuracy of LCCAs. When applied to Colorado, the forecasting model, on average, led to more accurate forecasts than current practice. In this example, the average error of the CSHub models 20 years prediction into the future was 46 percent and 32 percent less than current no change assumption.

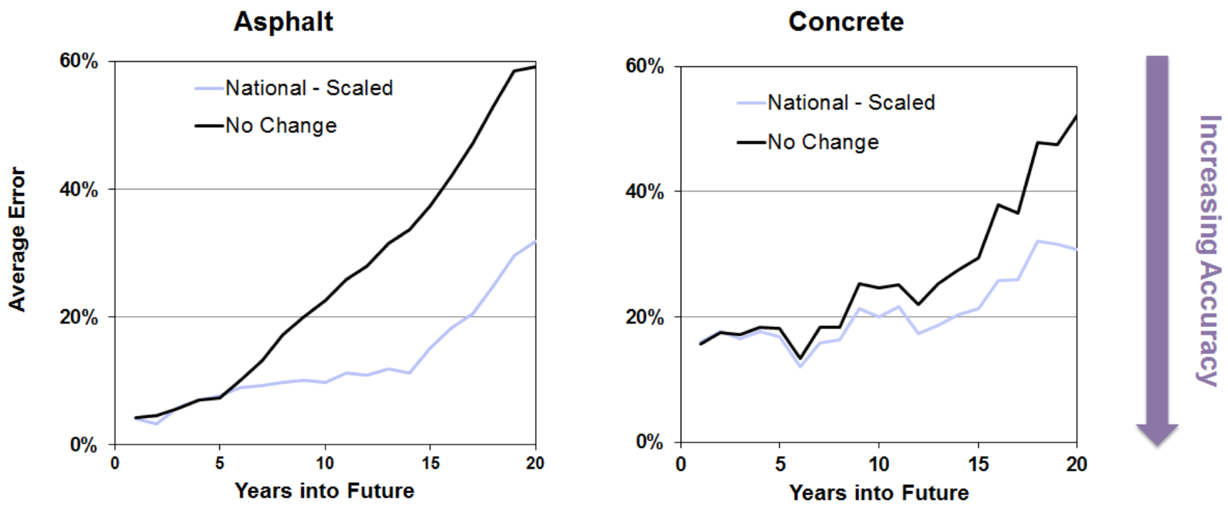


Figure 7: The average error of price forecasts made between 1976-1990 for Colorado using current-practice (labeled "No Change") and CSHub method (labeled "National – Scaled"). The left plot is for asphalt, and the right plot is for concrete.

3. HOW TO ACCOUNT FOR PAVEMENT VEHICLE INTERACTION (PVI) IN DEVELOPING USER COST CALCULATIONS

User's costs are costs incurred by the users of a facility and are typically based on the vehicle operating costs. They are sometimes included in a project level LCCA to account for the differential cost impacts that alternative solutions may have on the public. Historically, they have been calculated based on the value of time and idling cost caused by traffic delay in maintenance and rehabilitation work zone's when comparing different pavement alternatives.

Pavement-vehicle interaction or PVI is the study on how excess rolling resistance between the pavement and the vehicle. impacts fuel usage. The details on PVI are covered extensively in reference (Mack, Akbarian, F.J., & Louhghalam, 2018), but as an overview the three pavement structural and surface property mechanisms that contribute to PVI are pavement roughness, surface texture, and pavement deflection due to loading. Simply, to maintain a constant speed in the presence of such resistive forces, the vehicle engine must compensate by outputting extra power and consuming excess fuel in the process.

Much like the economics studies, PVI has been a major focus of research at the MIT CSHub; but it has historically only been used in a Life Cycle Assessment that looks at the environmental impacts. In one part of a study with the Minnesota Department of Transportation (MnDOT), MIT took the PVI results and instead of converting the excess fuel usage to increased greenhouse gas emissions, they converted the excess fuel usage to PVI roughness and PVI deflection user's costs (no surface texture effects) so that they could be included within a LCCA, along with the work zone user's costs (Akbarian, Swei, Kirchain, & Gregory, 2017). It is important to note that although these PVI impacts are small for a single vehicle, their aggregated impact for a high-volume roadway have been shown to surpass other factors contributing to the pavement life cycle.

Deflection Induced PVI User's costs. The impact of Deflection Induced PVI User's costs is calculated based on recent research from MIT that now enables the quantitative assessment of the impacts that pavement structure, vehicle weight, and climatic characteristics have on a vehicle's fuel consumption through mechanistic models (Louhghalam, Akbarian, & Ulm, 2014), (Akbarian M. , 2015). The excess fuel consumption caused by deflection-induced PVI is evaluated for asphalt and concrete pavements as a function of subgrade stiffness, pavement stiffness, thickness, temperature, vehicle axle load, speed, and relaxation time. Relaxation time represents the pavement's viscoelasticity and its relationship with temperature and load time is captured for both asphalt and concrete materials.

Roughness Induced PVI User's costs. Roughness-induced PVI vehicle fuel consumption is evaluated using the Highway Development Management 4 (HDM-4) model, originally developed by the World Bank in 2001 and later calibrated to U.S. vehicle conditions in 2012 (Chatti & Zaabar, 2012; Bennett & Greenwood, 2001). The road roughness metric in HDM-4 is the international roughness index (IRI), evaluated from pavement profile measurements as the accumulated vertical motion along the road length, with units of slope. In addition to IRI, the HDM-4 model requires a reference roughness after construction or maintenance (IRI_0) here selected as 1 m/km (63 in./mi) to remain consistent with HDM-4's calibration baseline. Moreover, the roughness model accounts for vehicle type and vehicle speed in estimating the instantaneous increase in fuel consumption caused by roughness [a simplified form of the HDM-4 model and the calibration factors are provided in (Akbarian M. , 2015)]. The assumed cost of excess gasoline and diesel consumption for deflection- and roughness-induced PVI are consistent with HDM-4 model assumptions and are respectively equal to $3.63 and $3.97 per gallon.

Traffic Delays Caused by Work Zone Closures. Work Zone user's costs are calculated based on the FHWA's work zone road user cost economic analysis concepts that calculate traffic delay and the vehicle operating costs (Mallela & Sadasivam, 2011). The analysis contains traffic delay contributions from the time required to decelerate into and accelerate out of the work zone, the time added because of lower speeds in the work zone, the time spent stopping, and the time spent in queue. The number of passenger cars and trucks affected by each delay type during the maintenance and rehabilitation activities is calculated based on the hourly demand, free-flow capacity, work zone capacity, and queue rate to determine the total delay time for all vehicles. The associated added cost is calculated based on the hourly value of travel time, equal to $17 and $27 per person-hour for a passenger car and truck, respectively (MnDOT).

To compare the magnitude of the different sources of user's costs, MIT worked with MnDOT to evaluate a 11.7 km (7.25-mi) pavement that needs major rehabilitation and is planned in two lengths of 1.56 km and 10.1 km (0.97 and 6.28 mi.) Three possible rehabilitation scenarios are studied for each project length: a mill and 100 mm (4.0-in.) asphalt overlay with asphalt shoulders, a 150 mm (6-in) concrete overlay with asphalt shoulders, and a 150 mm (6-in) concrete overlay with concrete shoulders. The maintenance and rehabilitation activities were based on MnDOT standard LCCA policies and the predictions of pavement IRI were provided by the Minnesota DOT based on historical pavement performances for thick asphalt and concrete pavements.

Figure 8 presents the user costs associated with traffic delay, roughness-induced, and deflection-induced PVI impacts on passenger car and truck fuel consumptions. Since the dominating PVI impacts are independent of road shoulder type and are a function of road surface conditions and structural properties, the concrete overlay alternatives are assumed to have the same user costs. Any small difference in the results of these scenarios would be due to the traffic delay caused by maintenance of the asphalt concrete shoulders. The upward trend of the PVI-induced costs is associated with increasing road IRI levels and passenger car and truck traffic growths. It is observed from Figure 8 that roughness-induced PVI dominates the associated user costs, followed by deflection induced PVI, and finally traffic delay users costs during rehabilitation.

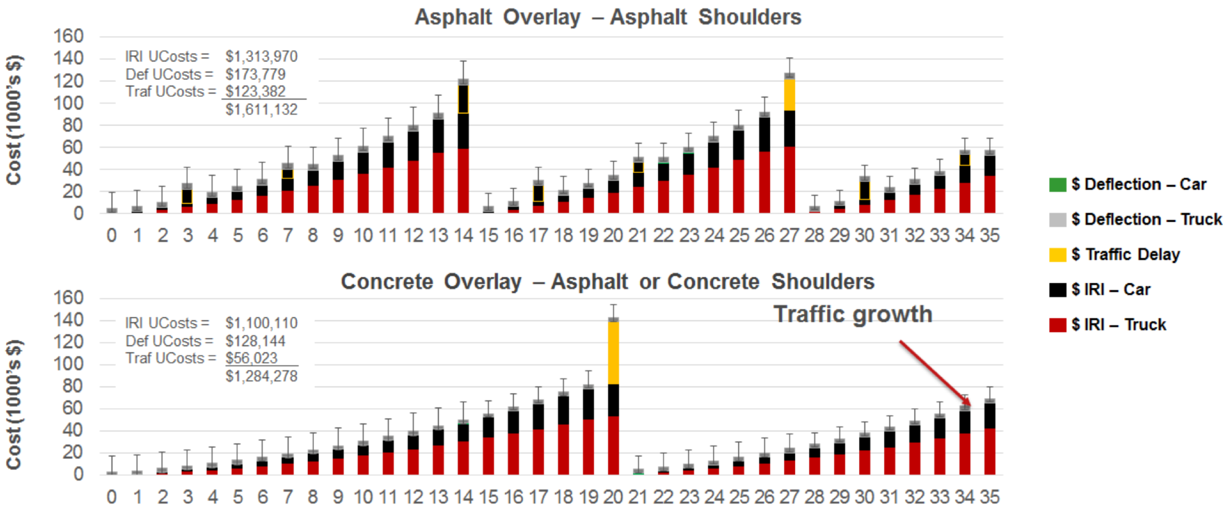


Figure 8: User cost associated with traffic delay, roughness-induced, and deflection-induced PVI for scenarios.

4. HOW INTER INDUSTRY COMPETITION IMPACTS ON PAVEMENT UNIT PRICES

A basic tenant of economic theory is that when sustained competition exists in a market, the price for similar goods is expected to go down. However, the current state of competition in the US pavement market (and probably most countries) is that there is little inter-industry competition. In an analysis of Bid Data from 2009-2014, it was found that well over 90% of all paving projects are bid with only one material (Oman). It was also found that amount spent on concrete and asphalt paving materials varies greatly from state-to-state. An analysis of spending over a five-year period showed that no state has spent less than 70% of their paving budget on asphalt pavements for DOT projects and that there are several states where virtually no competition exists between these two paving industries (Figure 9).

To see if competition does impact the costs of paving materials, MIT initiated a research project to find out which factors have the most influence on pavement prices by statistically analyzing historical pavement construction data in the U.S. It was theorized that while competition among contractors that construct a single pavement type does provide some competitive benefits; competition between pavement industries brings additional contractors and another level of competition to the supply chain, which fosters innovation and lowers the average unit prices for both asphalt and concrete pavements. If true, then agencies could purposely use / bid both concrete and asphalt on their pavement projects to create competition across paving industries and as well as among contractors to lower costs and bring significant savings to the DOTs and taxpayers.

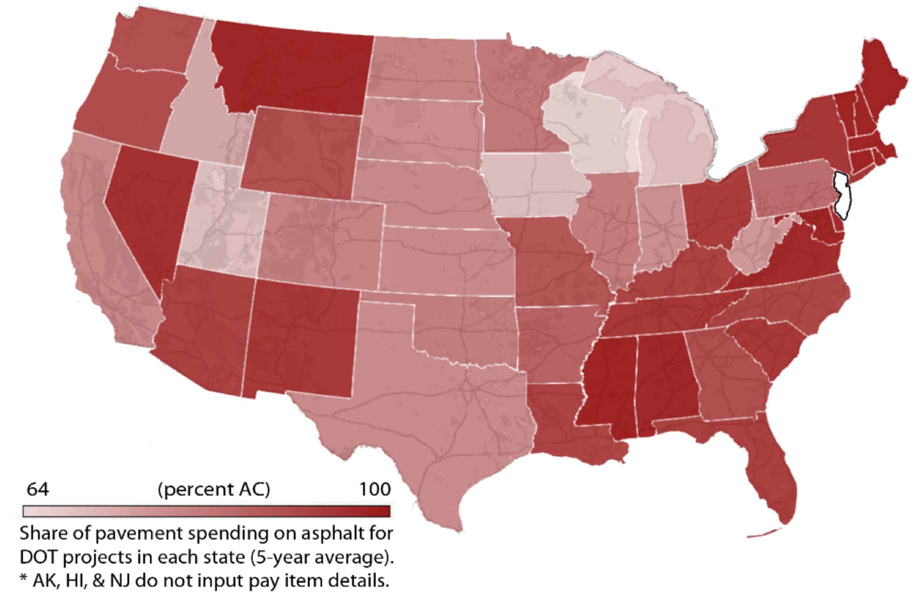


Figure 9: Share of pavement spending on asphalt for DOT projects in each state (5 year average). Alaska, Hawaii, and New Jersey do not report pay item details.

To determine which factors had the most influence on pavement prices, MIT statistically analyzed historical pavement construction data in the US using the Oman BidTabs database. They collected 10 years of pavement construction bid and materials pricing data from 47 state DOTs, which represented approximately 298,000 pay items from 164,000 jobs. These items were then filtered to exclude activities that were not directly relevant to paving (e.g., curbs, drainage, etc.). Next, statistical models were developed to determine what factors have a statistically significant influence on paving material costs, including items like the amount of paving material used in a job, the number of bidders on a job (a metric of intra-industry competition), and the average share of spending in a state on concrete (a metric of inter-industry competition). Finally, bid prices were adjusted to account for year-to-year price change.

Figure 10 shows the factors that MIT determined had the most influence on paving material bid prices. For asphalt paving materials, the most influential factors impacting bid prices are market size, followed by inter-industry competition, project size, intra-industry competition, and the presence of price-adjustment clauses, which are used primarily for asphalt paving prices. For

Figure 10: Statistical analysis results showing factors impacting asphalt and concrete initial bid prices

concrete paving materials, the most influential factors driving bid prices are project size, followed by inter-industry competition, market size, and intra-industry competition. The key thing to note is that inter-industry competition is a key driver for lowering both concrete and asphalt pavement bid prices.

Once MIT determined the key factors, they used their statistical modelling to estimate the impact that increasing inter-industry competition would have on paving prices (Figure 11). The estimates demonstrate that increasing inter-industry competition corresponds to a decrease in paving material prices and states that proactively invest in more competitive pavement spending over an extended time period will likely pay significantly less for both paving materials.

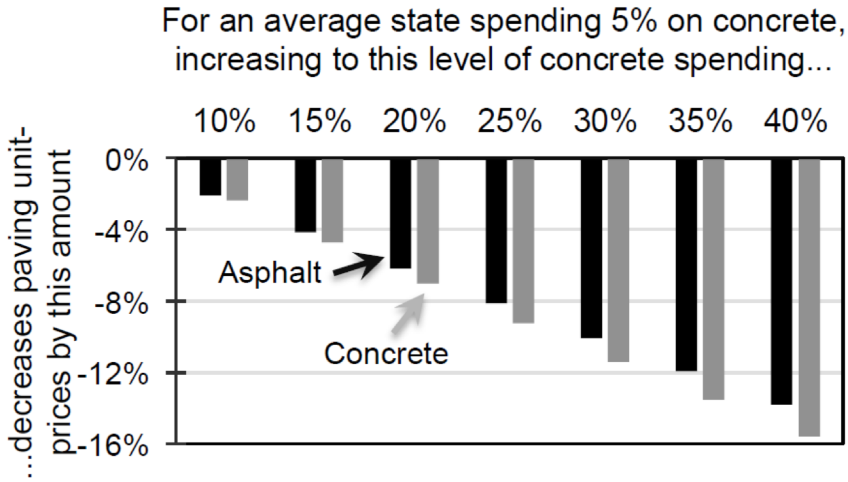


Figure 11: Estimated impact of increased inter-industry competition on asphalt and concrete paving prices

5. HOW ALLOCATION CHOICES AND PAVEMENT TYPE DIVERSIFICATION LEADS TO IMPROVED PAVEMENT NETWORK PERFORMANCE.

Federal and state transportation agencies use pavement management systems (PMS) to evaluate the performance of their pavement networks, and to assist in allocating resources for across the network for the planning and prioritization of pavement projects. These systems typically include a database of current and historical pavement conditions, pavement structure, and traffic for segments in the network. They may also include algorithms that predict future pavement performance, which can be used to estimate future economic requirements, and allocate resources for pavement improvement projects.

Despite recent enhancements to these systems, several gaps exist in the current frameworks. For example, network level models typically do not consider pavement structural and material information despite their importance to roadway deterioration. Similarly, these existing network level tools ignore the present and future cost uncertainty for project-level decisions that was described in Section 2. Finally, many agencies use a limited set of non-pavement specific maintenance, rehabilitation, and reconstruction (MRR) techniques to maintain their pavement networks. The fact is that there are numerous alternative asphalt and concrete techniques available and expanding the set of techniques used by agencies has numerous potential advantages including improving the performance of the network, lowering costs, and reducing risk associated with future fluctuations in material prices.

To address these gaps, MIT is developing tools and processes to help transportation agencies better model their roadway performance and impact of allocation processes. To do this, MIT created a probabilistic network analysis model to calculate the optimal allocation of resources for pavement improvement activities in a network (Figure 12). This model is unique in that it accounts for uncertainty in both pavement deterioration and the future cost of maintenance actions, which enables agencies to understand the risk associated with predictions of pavement performance and the costs of MRR activities. Another advancement is that MIT developed a simple heuristic approach

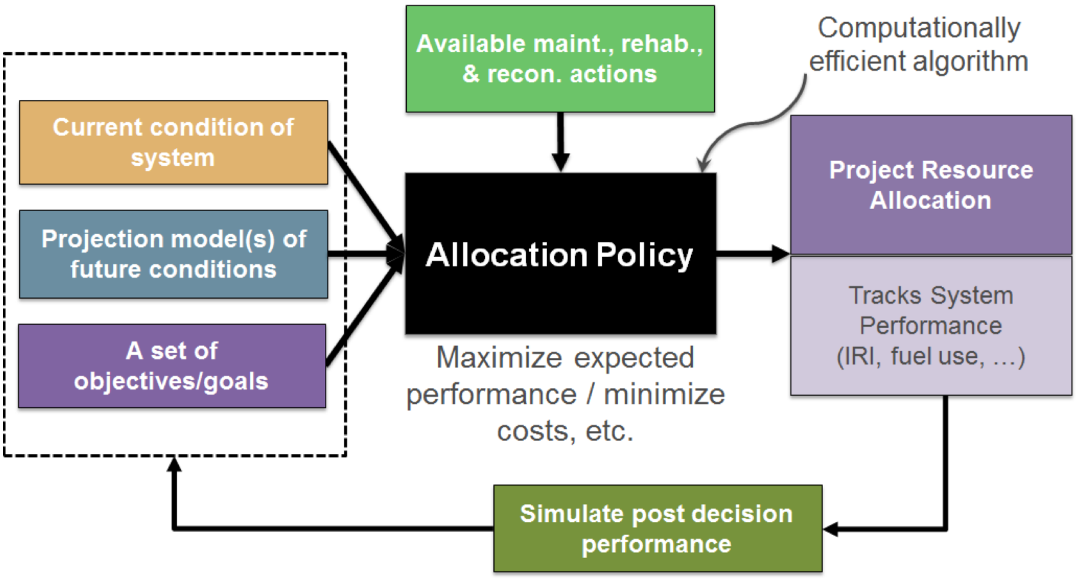


Figure 12: MIT Decision-support tool for pavement management systems

that has been shown to lead to near optimal decisions in a fraction of the computational time of other approaches. This significant reduction in computational time allows agencies to accommodate design-specific information and explore the impacts of flexibility with a more diverse set of MRR techniques, which will enable agencies to proactively deal with an uncertain future and other sources of variation. Such diversification should allow decision-makers to more easily adapt their investment choices as information about the state of their system becomes available over time, similar to a diversification strategy used in financial portfolios.

To check the fidelity of the model, MIT implemented it on a case study of Virginia DOT's interstate pavement network. This network is composed of approximately 3,000 pavement segments that traverse more than 8000 lane-km (5,000 lane-miles). VDOT, like many others, currently maintains its roadway system primarily with asphalt-based technologies and ignores uncertainty related to material prices and pavement deterioration. The analysis performed by MIT looked at how the pavement network performance would be different based on modifying the current process to account for the following 3 items and using an allocation policy that maximizes expected performance / minimizes cost:

1. Increasing the types of available rehabilitation actions to include the following concrete and asphalt alternatives: Diamond Grinding, Mill and Fill with thin asphalt overlay; thick asphalt overlays, concrete overlays; new concrete pavement, and new asphalt pavement.
2. Using material specific pavement deterioration models to project for the future conditions, expressed by IRI.
3. Using material specific pavement cost models to project initial and future costs of the various activities based on the process outlined in Section 2 above.

Figure 13 shows the results from the analysis and one can see two important conclusions. First is that the asphalt only option is affected by high variability in performance. This is primarily due to the variability in price throughout the lifecycle, which impacts how much of the system can be touched in years of high prices. The second and more important finding is that a system that utilizes both asphalt and concrete tends to outperform scenarios that use only concrete solutions or only asphalt solutions. This is partly due to the consideration of a larger range of designs and rehabilitations with different costs and performance levels. However, a more important reason is that in some of the simulations, the cost of concrete and asphalt grow quite differently and when that happens, the ability, or option, to change between materials as uncertainty arises proves to be quite significant in improving long-term performance.

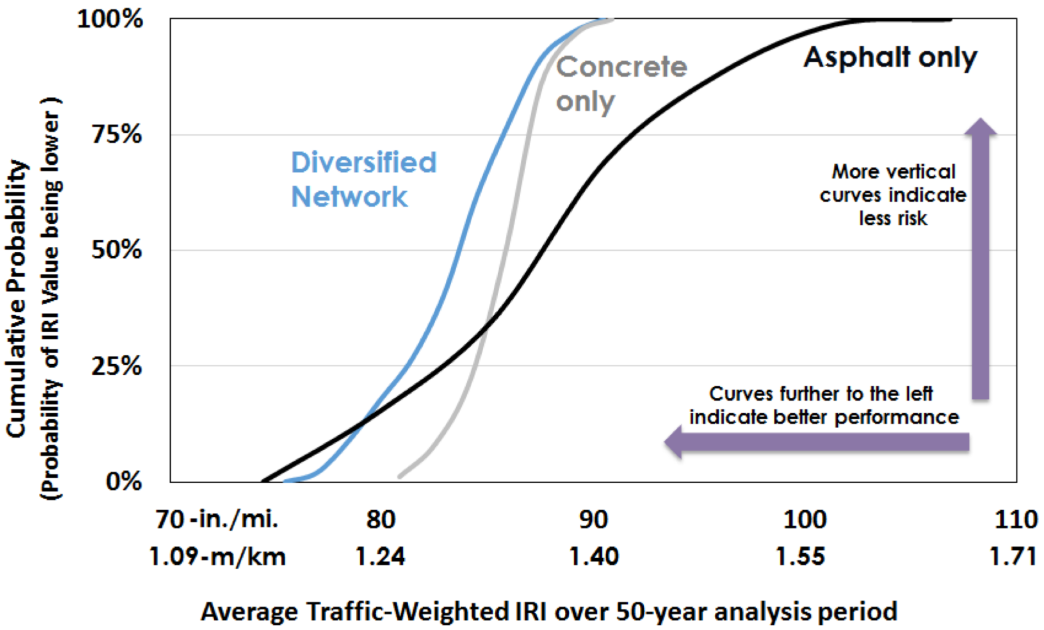


Figure 13: Network Analysis results showing that a diversity of MRR alternatives leads to enhanced network performance:

Another way to look at the results is that if an agency wants to achieve a given designed performance level (eg IRI = 140 m/km (90 inch/mi.)), the agency can achieve this desired performance goals, on average, at a cost reduction of 10% by incorporating multiple pavement MRR techniques. Again, much of this value stems from the ability to alter investment strategies at moments of spiraling costs for some MRR actions and suppressed price levels for others. Together, these findings suggest that the benefit from utilizing a larger range of paving MRR strategies by a transportation agency could be much higher than agencies realize using the conventional approach of current pavement management systems that does not account for uncertainty.

6. SUMMARY

In 2009, the US cement and concrete industries established the Concrete Sustainability Hub at the Massachusetts Institute of Technology to develop and find breakthroughs that will lead to more sustainable and durable pavement infrastructure and buildings. With regards to the economics of pavements, MIT found that there are several opportunities to improve both the project-level and network-level pavement type selection practices, which will potentially lower expenditures and improve the pavement network performance.

On the project level, the key results MIT found were:

- The current assumption of that all materials grow with the general rate of inflation (aka the “no change” model) is seriously flawed and not accounting for differences in inflation can bias the LCCA results.
- Using long term concrete and asphalt price forecasting models to estimate future costs in a LCCA outperformed conventional assumptions and existing methods. When applied to Colorado, MIT’s forecasting model decreased the average error for price projection 20 years into the future by 46% and 32% for asphalt and concrete respectively when compared to the current practice.
- Pavement Vehicle Interaction user’s costs are much greater than traffic delay user costs. Based on two case studies using typical pavement designs and performance data from Minnesota, it was observed that roughness-induced PVI dominates the associated user costs, followed by deflection induced PVI, and finally traffic delay user’s costs during maintenance and rehabilitation.

At the network level, MIT determined:

- Increasing inter-industry competition corresponds to a decrease in paving material prices and agencies that proactively invest in more competitive pavement spending over an extended period of time will likely pay significantly less for both paving materials.
- Based on an analysis of approximately 298,000 pay items from 164,000 jobs; MIT determined that if an agency were spending 5% on concrete and they increased their level of concrete spending to 30%, they would see a decrease in concrete and asphalt unit prices by about 10% and 11% respectively.
- A diversified pavement network (one that uses both concrete and asphalt solutions) performs better for the same total pavement expenditures when compared to a pavement network made up of only one material. The primary reason for this stems from the ability to alter investment strategies at moments of spiraling costs for some MRR actions and suppressed price levels for others.

As DOTs continue to search for effective methods to maximize performance of pavement segments in the face of limited resources and a highly uncertain future, it is hoped that the information, tools and methods developed at MIT and outlined in this paper can help meet those needs.

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