

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, two areas of focus have been on how the economic practices used in the pavement type selection process can be improved and how inter-industry competition (competition between industries) can lower agency pavement costs. With regard to the economic practices, MIT has focused on how the Life Cycle Cost Analysis (LCCA) process can be improved so that the results are more representative of the agency's cost. With regard to competition, MIT has shown that sustained and viable competition between paving industries can lower bid prices. The goal of this paper is to summarize the relevant MIT CSHub pavement economic and competition research to date.

INTRODUCTION

The Concrete Sustainability Hub (CSHub) at the Massachusetts Institute of Technology (MIT) was established 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 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, an area of focus has been on the economic analysis practices used in the pavement type selection process so that they more accurately reflect the most likely expenditures for an agency. For example, MIT has determined that paving materials (asphalt and concrete) inflate at different rates, and if not taken into account; this will inadvertently bias the results, which can make an agency's LCCA process flawed. MIT also determined that sustained and viable competition between paving industries results in lower bid prices and can be used in a way that leverages the free market to the advantage of the state and the taxpayer. 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 inter industry competition leads to lower pavement material unit prices.
- How allocation choices and pavement type diversification leads to improved network pavement performance.

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

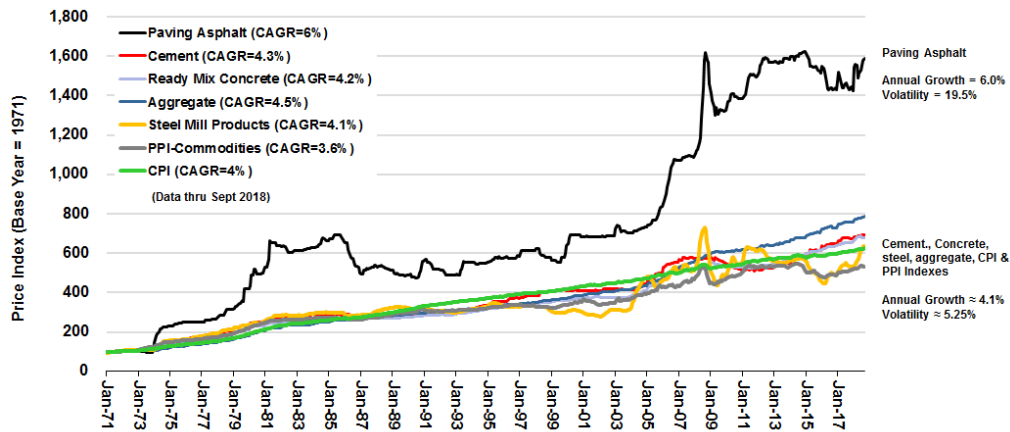


Figure 1 – Comparison of annual inflation rates for pavement construction materials and the general rates of inflation (PPI and CPI) since 1971

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 on a given project to determine which pavement design (asphalt or concrete) is most cost effective. However, to be meaningful, credible, and reliable, 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 J. , 2012) demonstrate that the practice of assuming that all paving material prices grow at the general rate of inflation (also known as “no real price change”) is inconsistent to the historical price change of these commodities over time. Ignoring this does bias the cost estimates in the LCCA and potentially leads to costly overruns on both the project and network level.

Escalation: The difference between a specific product’s inflation and the general rate of inflation is known as *real price change* and the economic procedure to account for its impacts on future material cost estimates is called *escalation*. Note that real price change is also known as changes in relative prices, differential inflation rates, material specific inflation, and constant dollar changes. All these describe the same issue, and this real price change can either be an increase or decrease in future prices. 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:

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

where

e = escalation rate and n = year of activity

The reason to include real price changes in a LCCA is that its use has the potential to improve future cost estimates, thereby improving the LCCA results, reliability and credibility.

While escalation is an easy concept, some have argued for not using it in pavement LCCA's 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 improves the future cost estimates or is more accurate than using the last known price in perpetuity.

Addressing the first concern is relatively easy because it is not true. FHWA's LCCA Technical Bulletin, LCCA Primer, and Economic Analysis Primer all state something along the lines that "future cost and benefit streams should be estimated in constant dollars," which means accounting for real price changes (FHWA, 1998; FHWA, 2002; FHWA, 2003). These publications do recognize that the process can be difficult, but it does not mean the practice is not recommended.

It is also important to recognize that accounting for real price changes in the cost estimates for other agency's economic analysis procedures is a recommended, endorsed, and standard practice. 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 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).

With respect to pavements, in 2013 the Government Accountability Office (GAO) reviewed the FHWA LCCA procedures, and the practices used by 13 different states. While the GAO did not find any "errors" with the way states were doing their LCCAs, the report (GAO, 2013) did identify that states' need to improve the cost estimates used in their LCCAs and recommended that FHWA update its guidance to fully incorporate the GAO's best practices cost guide to develop more reliable, high-quality cost estimates (GAO, 2009). These guidelines include very specific guidance on accounting for inflation when developing cost estimates.

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 shows the five recommended steps to performing a LCCA. The bullets in red italics are the additional steps needed to account for real price changes.

MIT's Real Price Forecasting Research: The focus of the MIT's research has been on items 2 and 3 – developing real price forecasting models" that better predict future cost estimates 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 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.

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

| | |
|--------------------------|---|
| Establish LCCA Framework | <ul style="list-style-type: none"> • Establish analysis period • Establish how inflation will be treated (nominal or real) <ul style="list-style-type: none"> • 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 | <ol style="list-style-type: none"> 1. Establish Alternative Pavement Strategies 2. Determine Rehabilitation Activity Timing 3. Estimate Agency and User Costs (UC are optional) <ol style="list-style-type: none"> a. Initial Construction Costs b. Rehabilitation Costs <ul style="list-style-type: none"> • Escalate cost to the activity year to account for “Real Price” Changes 4. Compute Life-cycle Costs 5. Analyze the Results |

To develop their real price forecasting models, MIT proposed developing a life cycle cost estimating approach that independently modeled the expected cost of the materials using a probabilistic approach to account for risk and uncertainty. That is, most forecasting models are deterministic, relying on past behavior to construct a single-point forecast of the future. While useful, the primary weakness with deterministic models is that they do not consider uncertainty and random events such as earthquakes or political instability, and as such they fall short and under- or over-predict actual values.

The MIT CSHub price projection model uses a probabilistic approach to account for uncertainty and risk for the 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 which is 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, that can account for the long-term macroeconomic trends. The problem is that it is on annual basis and is not as plentiful as the monthly BLS commodity data.

As such, and based on the data availability, MIT used a 2-step approach that first used the extensive but short term (30 year) BLS monthly data to show that the paving material commodities and their constituents behaved similarly and had a price trend relationship thru a process called cointegration. An example of this is shown in Figure 2, which shows the price of asphalt has followed, or is cointegrated with the composite trend its constituents of sand, gravel, crushed stone and oil.

MIT has performed this analysis two different times – one in 2013 (based on data until 2011) and again 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

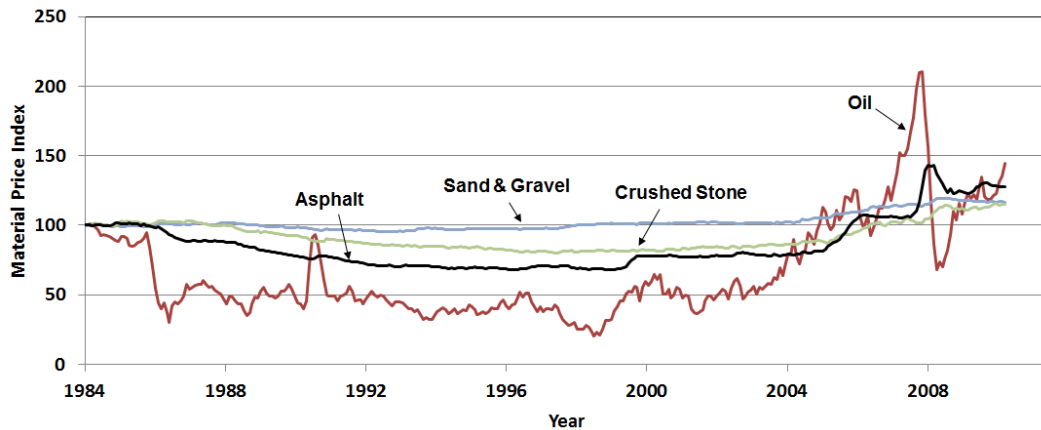


Figure 2: Example of how a commodity price (asphalt) follows the composite trend of its constituents and can be used for the basis for price projection models

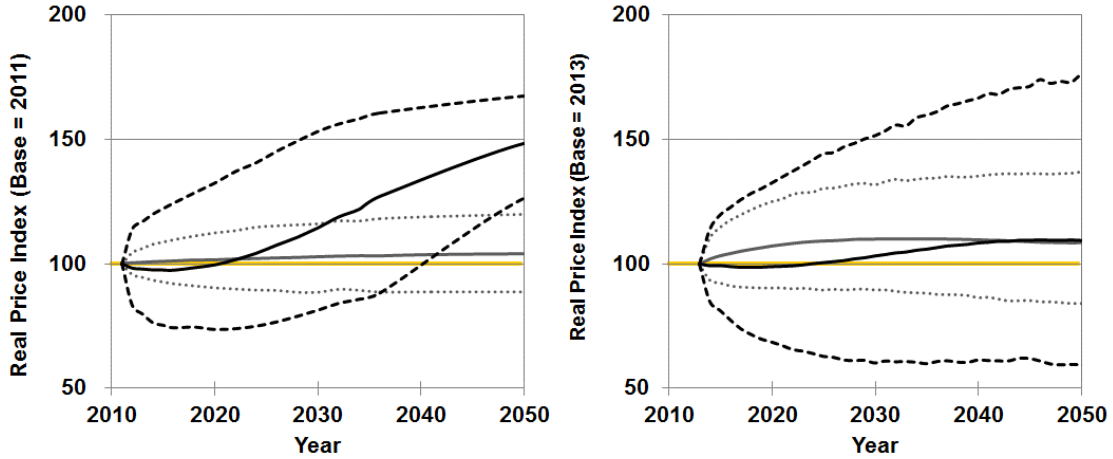
determined that asphalt was cointegrated only with crushed stone and oil (sand dropped out) while concrete was still cointegrated with crushed stone and cement.

The second step was then to use these short-term relationships and the annual, long term (100 year) historical constituent data to develop long term price trend forecast models that capture the long-term macroeconomic trend of the concrete and asphalt materials themselves. This approach allowed MIT to build forecasting models for asphalt and concrete prices that greatly improved the quality of the final results. Based on the data analysis, it was determined that cement follows a slow, yet present, mean-reversion characteristic to a constant mean, whereas crushed stone was found to follow a geometric Brownian motion process. Oil was found to be best modeled with a simple quadratic mean-reverting process to a continually shifting mean, which accounts for the continually shifting marginal cost of oil production.

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). For complete details of the process and model development, see references (Swei, Gregory, & Kirchain, 2013; Swei, Gregory, & Kirchain, 2015; Swei, Gregory, & Kirchain, 2017; Mack, Gregory, Kirchain, Akbarian, & Swei, 2018)

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 3 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. Specifically, the 2013 asphalt and concrete mean models had very different mean projections, 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 seen that while the expected volatilities between the 2013 and 2017 model for both the concrete and asphalt materials increased, the asphalt variability increased (became wider) much more than the concrete variability. These changes indict why the models should be updated on a regular basis.



(a) 2013 Analysis

(b) 2017 Analysis

Figure 3: Probabilistic real-price projection for concrete (gray) & asphalt (black). Dashed lines are the 5th/95th percentile of the forecasts, and solid lines are the mean expected price.

Once MIT had developed their real price forecasting models for paving materials, they compared the relative performance of the Price Projection Models to current practice, or “no change model” to determine if the accuracy of the future price projections produces better results (item 3 in the list above for not accounting for real price projections). 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 it can be used to quantify the performance of different models as well as to contrast the results with the standard no change models. MIT performed backcasting in two 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, but it needs to be pointed out that both backcasting analysis showed that the price projections models outperformed the standard no change models.

To evaluate the projection modeling 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

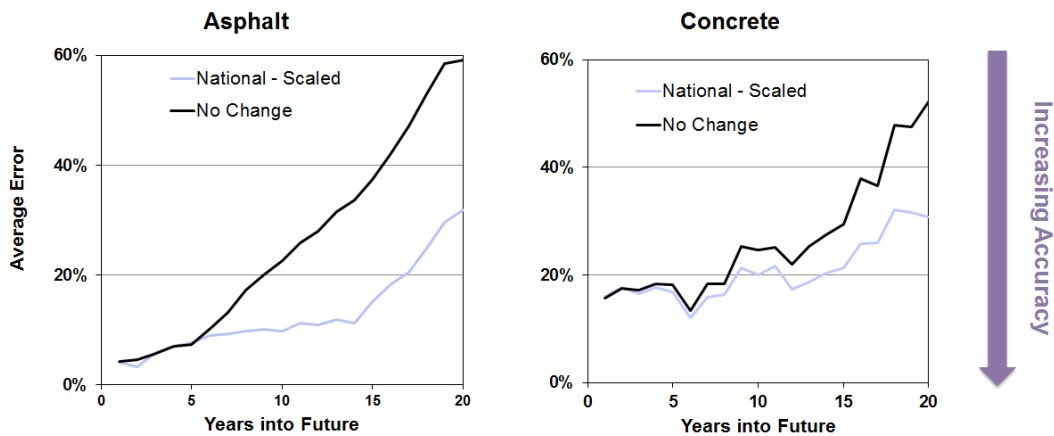


Figure 4: The average error of price forecasts made between 1976-1990 for Colorado using current-practice (labeled “No Change”) and CSHub method (labeled “National – Scaled”). The left plot is for asphalt, and the right plot is for concrete.

over the existing assumption of constant real prices with no escalation (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 scaled to the state level (the 2013 model was used as this research was done in 2014). This approach was used because the national data gave the shape of the model while the state data sets gave the starting point. The comparisons were based on 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 4 shows the results of the analysis comparing the two approaches for predicting asphalt and concrete costs 20 years into the future. As can be seen, when applied to Colorado, the MIT CSHub material specific projections reduced the average error for asphalt and concrete by 46 percent and 32 percent, respectively, vs. the current no change assumption. This shows that forecasting cost projections are a better practice than the current no change models and that its use will improve the accuracy of LCCAs.

INTER INDUSTRY COMPETITION IMPACTS ON PAVEMENT PRICES

A basic tenant of economic theory is that when sustained competition in markets exists, the price for similar goods goes down. However, the current state of competition in the US pavement market 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 the amount spent on concrete and asphalt paving materials varies greatly from state-to-state. An analysis of pavement spending on DOT projects over a five-year period found that no state spent less than 70% of their paving budget on asphalt pavements and that there are several states where virtually no competition exists between these two paving industries (Figure 5).

To see if competition does impact paving materials costs, 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 a second level of competition to the supply chain that fosters innovation and lowers the average unit prices for both asphalt and concrete pavements. If true, then agencies could purposely bid both concrete and asphalt on their pavement projects to create competition across

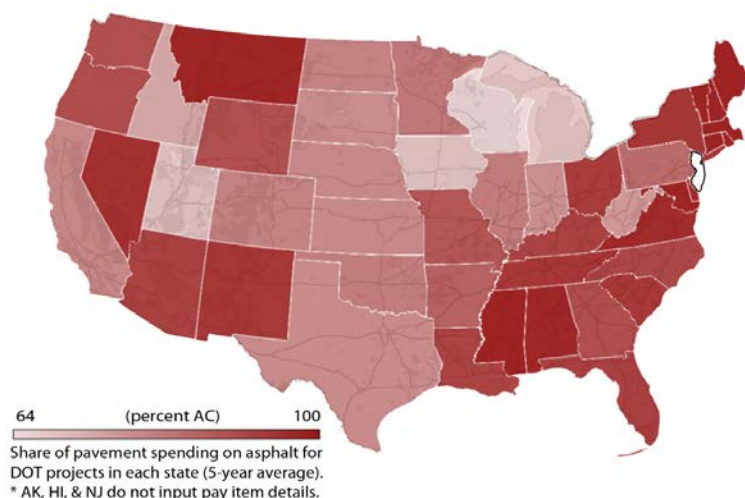


Figure 5: Share of pavement spending on asphalt for DOT projects in each state (5-year average).
 Alaska, Hawaii, and New Jersey do not report pay item details.

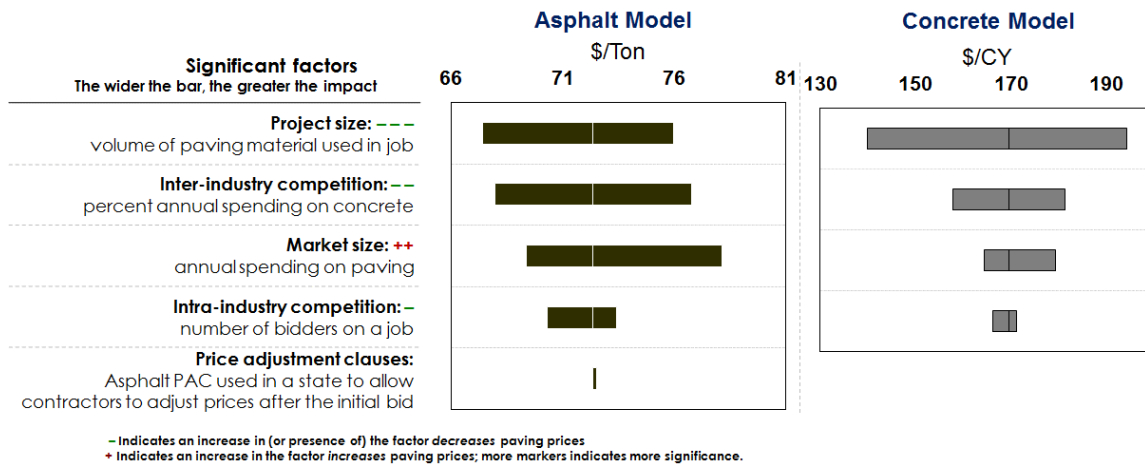


Figure 6: Statistical analysis results showing factors impacting asphalt and concrete initial bid prices

paving industries and among contractors to lower costs and bring significant savings to the DOTs and taxpayers.

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 (Oman). They collected 10 years of pavement construction bid and materials pricing data from 47 state DOTs that 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 analysis was used to determine what factors, such as 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) have a statistically significant influence on paving costs. Finally, bid prices were adjusted to account for year-to-year price change.

Figure 6 shows the factors that MIT determined had the most influence on paving material bid prices. For both asphalt and concrete, it can be seen that inter-industry competition the second most influential factors impacting bid prices (market size is first for asphalt and project size is first for concrete). Intra-industry competition (competition between contractors) is fourth for both.

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 7). The estimates demonstrate that increasing inter-industry competition corresponds to a decrease in paving material prices and states that proactively instill more competition between the concrete and asphalt industries will likely pay significantly less for both paving materials as shown in Figure 7.

HOW DIVERSIFICATION AND ALLOCATION PRACTICES IMPROVES A NETWORK'S 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 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.

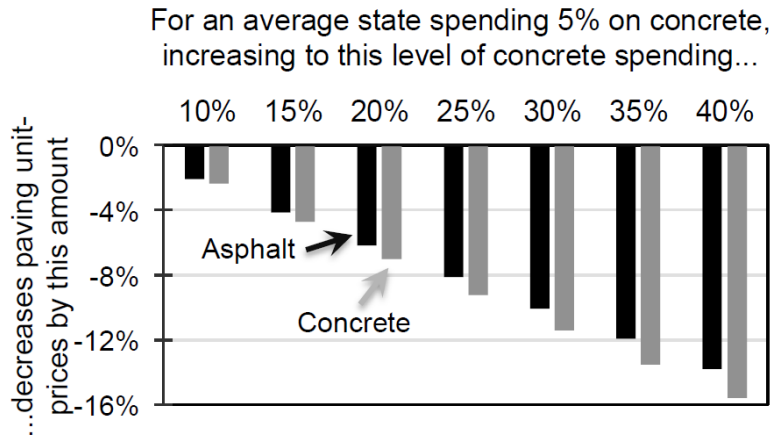


Figure 7: Estimated impact of increased inter-industry competition on asphalt and concrete paving prices

Despite recent enhancements to these systems, several gaps exist in the current frameworks. For example, network level models typically do not consider pavement structural (thickness) and material properties 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 the section on real price changes. 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 created a 2-step probabilistic network analysis model to calculate the optimal allocation of resources for activities at the pavement network level (Figure 8). 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 in how MIT determines the “optimal” solutions. In step 1, for each segment of the roadways, MIT uses a Monte Carlo simulation to determine what the top 2 to 3 best solutions are for each given section of roadway assuming that budget is not an issue. The idea here is that on any single project; the overall cost for any activity could be easily funded within the overall highway budget (e.g. 2 to 5-mile pavement project could be easily

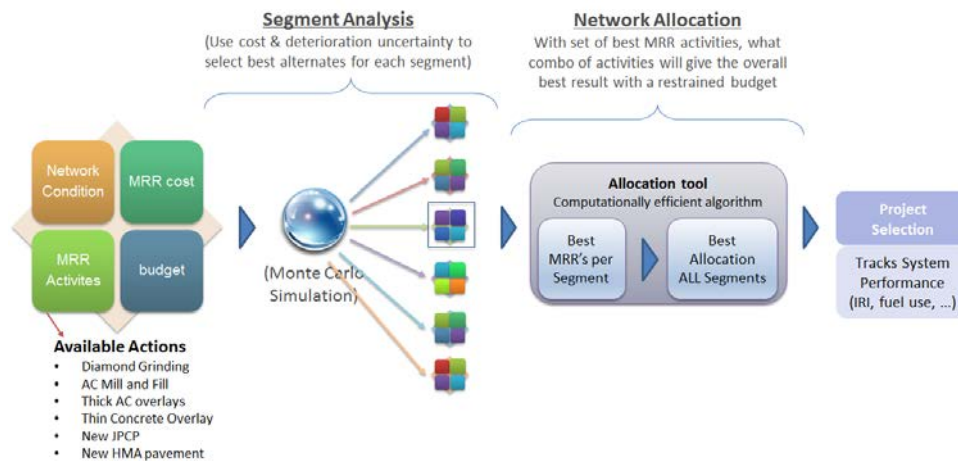


Figure 8: MIT Decision-support tool for pavement management systems

funded in a \$1B+ highway budget). The second step takes the set of best MRR activities and determines which segments to repair and what combination of activities to use will give the overall best result for the entire network within the DOT restrained budget.

The primary advantage of this approach is that it 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.

As an example of how this can be done, 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:

1. Increase and differentiate 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 Traffic Weighted IRI.
3. Using material specific pavement cost models to project initial and future costs of the various activities based on the process outlined above.

Figure 9 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 life cycle, 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

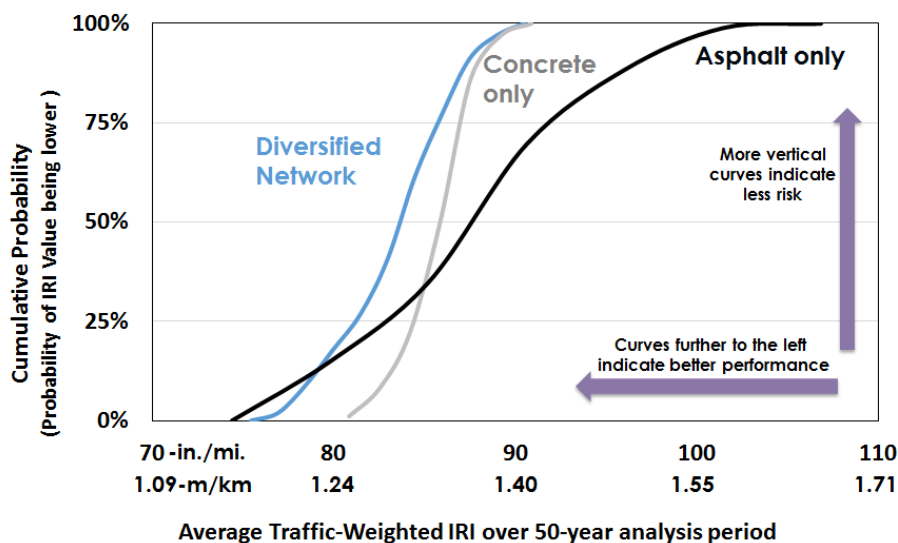


Figure 9: Network Analysis results showing that a diversity of MRR alternatives leads to enhanced network performance

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. The major takeaway of this 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 goal, on average at a cost reduction of 10%, by incorporating multiple pavement MRR techniques.

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 at the project level, MIT found that the current assumption 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. MIT then developed long term concrete and asphalt price forecasting models to estimate future costs in a LCCA and found that when applied to a case study in Colorado, MIT’s forecasting models outperformed conventional assumptions by 46% and 32% for asphalt and concrete respectively.

MIT next determined that increasing inter-industry (asphalt vs concrete) competition leads 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.

Finally, MIT looked at how a diversification of a pavement network (one that uses both concrete and asphalt solutions) leads to better performance 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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