American Association of State Highway and Transportation Officials
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Defining Cross-Asset Decision Making

A Discussion Paper

Developing Common Terms for Using Tradeoffs and Optimization to Allocate Transportation Investments








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As transportation organizations refine their management processes many are increasingly looking to cross-asset tradeoffs and optimization as the next generation of innovation to improve their transparency, credibility, and decision-making. However, as with many new fields there is a lack of common definitions and understanding regarding this topic. This paper briefly examines some of the concepts around optimization and cross-asset allocations or tradeoffs. It does not intend to be a primer on the topic, but rather it intends to begin a conversation that leads to a common set of definitions so that transportation officials can communicate more precisely as they discuss these topics.

Background

Optimization and cross-asset allocation are only two of recent transportation decision-making concepts entering the public sphere from the corporate world. Performance management, risk management, and even asset management have precedents in the business sector and are now expanding into public transportation agencies. In the corporate world, asset management refers to managing a portfolio of cash, stocks, bonds, and even real estate to maximize an investor's returns while managing risk. In transportation agencies, instead of managing the long-term performance of liquid investments such as stocks and bonds, the "portfolio manager" is managing investments in liquid physical assets such as pavements, bridges, buses, and rail lines. Both seek to maximize the long-term returns for their stakeholders while managing risk.

As asset management migrates from the private to the public sector it is not unexpected therefore that the related practices of tradeoff analysis and optimization would also soon follow. Decision makers seek tools to help improve decision making and document their tradeoffs. Traditionally, transportation agencies have made investment decisions for individual assets separately, due to restrictions associated with funding and/or limitations to the agency's ability to compare data objectively across asset types. Cross-asset allocation and optimization can improve decision making but they have important differences and each has strengths and weaknesses. The first step to understanding how to use them is to define them.

Sometimes, the terms "Cross-Asset Allocation" or "Cross-Asset Tradeoffs" are used interchangeably with "Cross-Asset Optimization." However they are different in key ways. All three relate to improved, fact-based decision making but they have several key differences.

This paper will consider the terms "cross-asset tradeoffs", "cross-asset allocation," and "cross-asset optimization" to be three distinct terms. They will be defined and described in the order of their complexity and quantified sophistication.

Cross-Asset Tradeoffs

Cross-asset tradeoffs represent the simplest and most common of the three concepts. It is defined here as, "the decision-making process by which resources from one asset class are transferred to another in order to maximize perceived utility." Please note the use of "perceived utility" as opposed to "measured or quantified utility." A "utility" in this definition can be simplified by thinking of it as any benefit defined by the user. It could be a level of physical infrastructure condition, such as a mile of smooth pavement, or a reduction in a ton of carbon emission, or an estimated reduction in crashes. A "utility function" then is the preference expressed given the expected risk and reward. If a department will pay more to prevent one crash than it would pay to reduce one mile of poor pavement, it demonstrates a higher utility for the crash reduction.

A cross-asset tradeoff example could be as follows. A state department of transportation has maintained its investment levels in pavements and bridges relatively stable over a number of years. During that time, bridge conditions have continued to improve and now exceed the national condition targets established in the Moving Ahead for Progress in the 21st Century Act (MAP-21). However, the department still has bridge concerns, such as a small but aging number of timber structures and a number of major bridges that are in good condition but are on the verge of declining into the "fair" condition. At the same time, the department's pavements declined noticeably. Although the number of "very poor" lane miles has not increased much in a decade, the number of "very good" miles has declined and the number of "poor" lane miles increased. Figures 1 and 2 illustrate these trends.

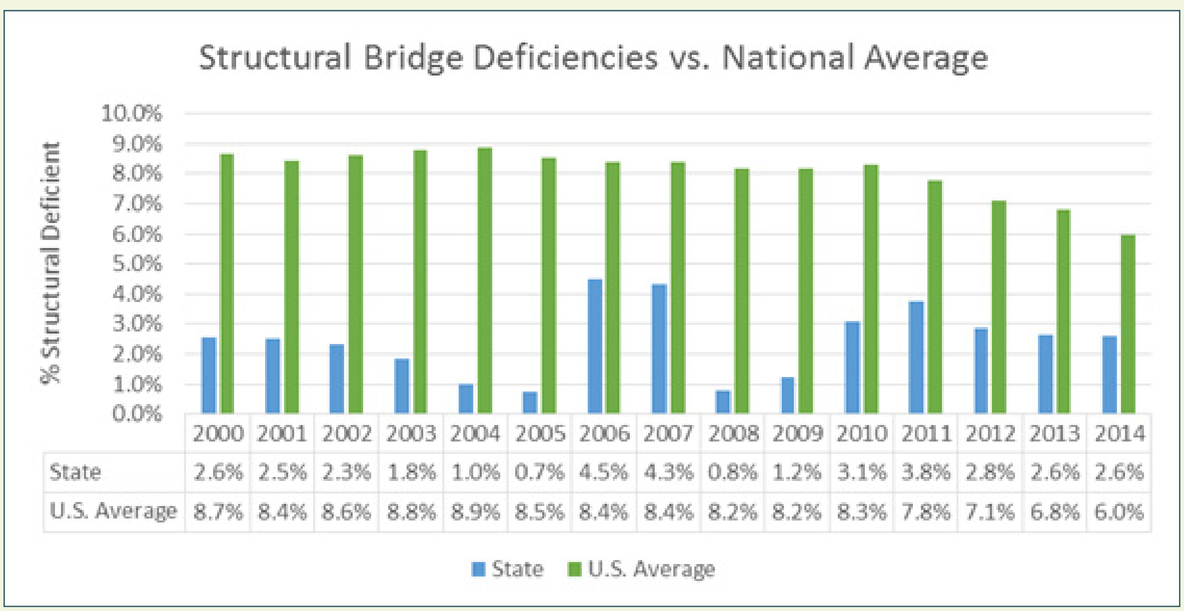

Figure 1. Bridge structural deficiencies remain well below national levels.

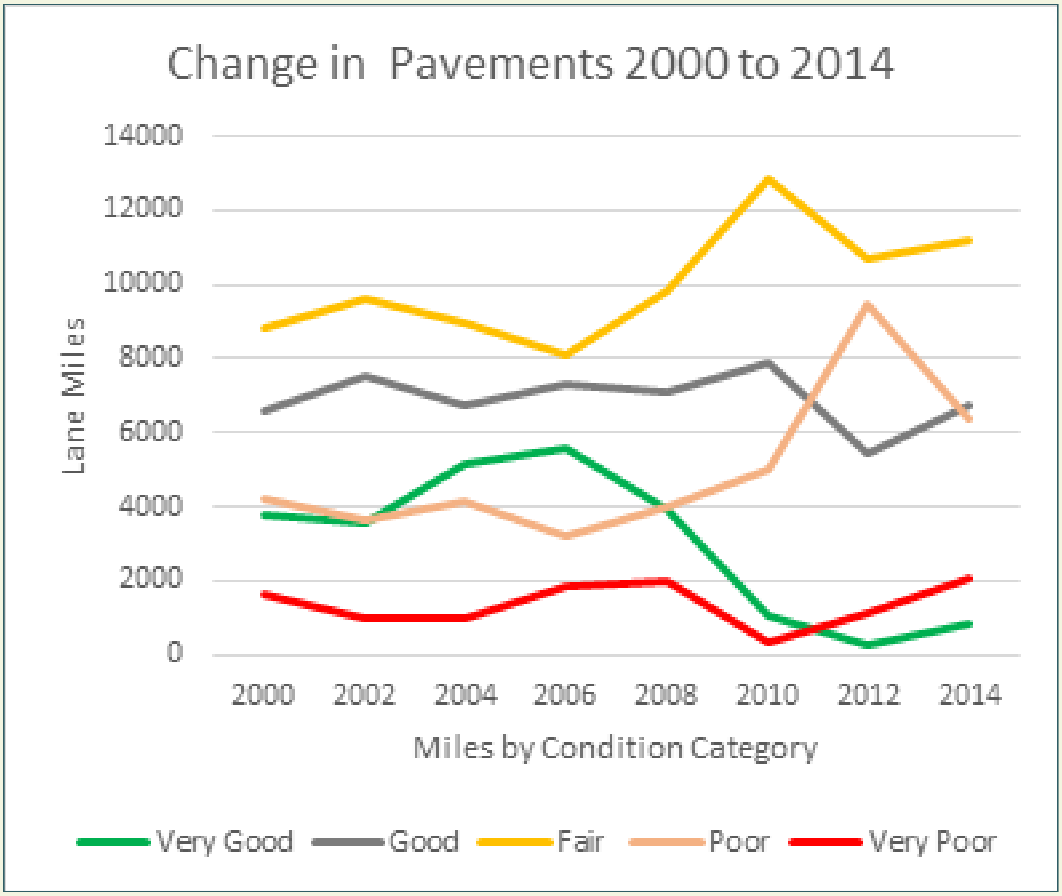

Figure 2. Pavement conditions declined overall with fewer "very good" miles.

Faced with static revenues and declining pavement conditions, the agency management can make a strategic decision to trade off bridge funds for increased pavement investments. In this theoretical example, it plans for a marginal reduction in overall bridge expenditures with the reduced amounts transferred to pavements. It chooses to reduce bridge spending overall but to maintain its focus upon replacing small timber structures and it chooses to increase investment in bridge preservation. Its strategy is to reduce long-term expenditures by replacing the high-maintenance timber structures and to reduce future costs of other bridges by its increased preservation program. For pavements, it plans to increase its preservation activities on its "good" pavements to prevent them from falling into the "fair" or "poor" category.

This example is typical of the kind of decisions that transportation executives have made for many years. It is a rational, fact-based decision and one they can document and justify. It is "data driven" in that agency officials are basing their action on the data showing that bridges are above the national targets while pavements are in decline. The decision is not a highly quantified one and it may be difficult for the decision makers to document how much benefit or utility their decision creates for the public. The objectives upon which the decisions are based are not specified and the decision may not be transparent without speaking with the decision makers. Although a rational decision, it is somewhat informal and dependent upon the judgment of a few individuals.

Cross-Asset Allocation

The next most sophisticated decision process would be cross-asset allocation. It is defined here as, "the decision-making process by which resources to multiple programs or asset classes are distributed based on the simultaneous quantified prioritization of utility." Differentiating it from cross-asset tradeoff is its simultaneous quantification of benefits of multiple programs or asset classes. Three types of cross-asset allocation are described here in the order to which they are likely to be familiar to transportation officials. Many variants of these three categories can be found in the literature. Each represents a rich and complex discipline which is highly condensed here.

Benefit/Cost

The first, and most familiar to transportation agencies is benefit/cost analysis (BCA). Agencies use it to rank order similar projects, such as safety projects or pavement treatments. BCA allows the costs and benefits of disparate attributes to be monetized, expressed as dollars, and then compared as ratios in which the benefits are divided by the costs. Projects with different attributes can be compared with a common denominator.

Although BCA is common at the project level, it is less commonly used to make tradeoffs between programs although it can be used for that purpose. Programmatic BCA is possible such as comparing the costs and benefits of higher pavement investments across a highway network compared to higher bridge investments, or comparing the return from additional safety projects versus mobility projects. Drawbacks of BCA at the program level are that broad assumptions may be needed to estimate benefits from an entire class of projects, such as the benefits aggregated from multiple pavement projects. The benefits of BCA are that it can illustrate that agencies are seeking to maximize resources, and it allows dissimilar projects and programs to be compared. Drawbacks can include difficulty in monetizing intangible benefits and in estimating project costs early in the planning process when scopes are undefined.

Multi-Criteria Decision Analysis

Like BCA, multi-criteria decision analysis (MCDA) weighs different benefits and impacts of options and combines them into a common denominator. With MCDA, however, the common denominator is not money but points or other numeric values. Evaluators chose a set of objectives, agree upon criteria and weights and then score the options. The multiplication of scores based on criteria times the weighting produce values for each alternative. The best scoring alternative can then be considered for selection. MCDA can be an alternative to benefit/cost analysis when either costs or benefits are difficult to monetize, such as when societal values influence a decision.

A very simple MCDA matrix could resemble Figure 3. An example such as this could be used to evaluate four different projects, or for altering budgets for four programs such as safety, pavements, bridges, and mobility. In this example four options are under consideration. Each is assigned points from 1–10 for two criteria each in the areas of safety impacts, pavement impacts, bridge impacts, and mobility impacts. The Total Safety Value score and the Total Pavement Value scores and so on are added. Those subtotals for each criteria area are multiplied by the weights, which are 4 for safety, 3 for bridges, 2 for pavements, and 1 for mobility. The values times the weighting provide final scores which are 96 for Option 1, 86 for Option 2, 79 for Option 3 and 72 for option 4.

This very simple example illustrates some of the benefits of MCDA. It allows members of a group to clarify their objectives and assign values to them by translating them into selection criteria. It also allows a group to declare its rank order of priorities through the weights. In this case safety is the number one priority followed by bridges, pavements and then mobility. Such a ranking system is transparent and leaves a clear record of decision of the criteria and weights that determined the selection. It is flexible, allowing criteria to be added. It also allows disparate criteria to be considered and translated into a common denominator.

The disadvantages are that it may not capture key issues such as cost effectiveness or risk. The process assumes that all options will be effective and are not subject to risk or uncertainty that they will fail to achieve their objective.

Multi-Criteria Analysis Matrix					
		Option 1	Option 2	Option 3	Option 4
Safety Criteria 1		2	1	1	3
Safety Criteria 2		4	3	4	5
Total Safety Value		6	4	5	8
Safety Weight	4				
Weighted Safety Score	(weight X value)	24	16	20	32
Pavement Criteria 1		6	5	7	5
Pavement Criteria 2		8	7	10	3
Total Pavement Value		14	12	17	8
Pavement Weight	2				
Weighted Pavement Score	(weight X value)	28	24	34	16
Bridge Criteria 1		10	9	1	1
Bridge Criteria 2		2	3	4	5
Total Bridge Value		12	12	5	6
Bridge Weight	3				
Weighted Bridge Score	(weight X value)	36	36	15	18
Mobility Criteria 1		3	3	4	5
Mobility Criteia 2		5	7	6	1
Total Mobility Value		8	10	10	6
Mobility weight	1				
Weighted Mobility Score		8	10	10	6
Weighted Ranking of the 4 Options		**96**	**86**	**79**	**72**

Figure 3. A multi-criteria analysis matrix.

Both a strength and a weakness is the significant sensitivity to the weights. Changing the weights can be used to test the sensitivity of options but decisions of how to weight categories can be the determinant of which option is selected.

MCDA evolved into its own discipline with scholarly journals, various schools of thought within the discipline, dozens of prioritization methods, and rigorous debate about the benefits of different approaches. This elementary example greatly simplifies the concepts that are more fully developed in the MCDA literature.

Risk/Reward-Based Allocation

This third method is modified from the Asset Allocation process commonly used on Wall Street to maximize an investor's returns and to limit risks to pre-determined thresholds or levels. It is called Risk/Reward Based Allocation and is defined as an investment strategy that seeks to apportion investment in different assets to maximize the overall utility while not exceeding acceptable levels of risk. This process is not commonly used by transportation agencies but is described here to illustrate how risk can be explicitly considered in cross-asset allocations. MAP-21 calls for a risk-based asset management program. Also, consideration of risk is considered a basic competency in much of the corporate world. Risk/reward based allocation is described here to illustrate how risk can be included into the decision-making process.

First, risk is defined as, "the positive or negative effects of uncertainty or variability on agency objectives." In a risk/reward decision process not only would possible benefits be considered but also factored into the process is the degree of uncertainty or variability about the potential outcomes. An example would be if a department reduced its pavement budget so that the miles of "fair" pavements increased and the number of "good" pavements declined. As a larger percentage of the pavement inventory enters the "fair" category there is more likelihood that a substantial number of them will fall into the "poor" category after a harsh winter, or under increased loadings or if the pavement models underestimate degradation. With a larger percentage of pavements in the "fair" category the department has more uncertainty in its pavement performance, more variability in its forecasts and greater overall risk of poor pavement performance. The money "saved" by reducing pavement expenditures can increase performance in another area but it brings more risk in another area, that being pavements. A risk/reward evaluation allows both the benefits of one investment to be weighed against the risks in another.

Figure 4 illustrates the concept. The curve is the Efficiency Frontier that represents the highest level of return possible given the corresponding risk. Investments that move to the right have more risk but generally also produce higher returns as shown on the vertical axis. An investor seeks to maximize returns for the level of risk he or she is willing to accept. The red dots represent the portfolios, or mixes of investments, that produce the highest return for the commensurate level of risk. The black dots represent inefficient portfolios. Each inefficient portfolio produces a return but they either incur more risk or produce less return than the better red portfolios.

For neither an investor nor a transportation agency is there one best "portfolio" or mix of investments. The best mix depends on the agency's investment objectives, the performance it needs to achieve and the amount of risk it is willing to accept. Both objectives and "risk appetite" can change. In times of economic crisis, agencies may take on more risk to achieve key objectives or they can decrease their risk exposure when their financial position improves. Both risk appetite or tolerance and objectives are situational.

For the theoretical agency mentioned in the cross-asset tradeoff example, a risk/reward exercise would be similar but more sophisticated than the Cross-Asset Tradeoff. In the Cross-Asset allocation exercise, the agency seeks to achieve the optimum results with its investments in each asset class. The "optimum" is key because the agency is not seeking to achieve the highest return in each class but the highest overall return from all classes while not exceeding the risk threshold. In our theoretical agency, it is not striving to achieve the highest possible bridge conditions because that would consume resources that could produce a higher return if shifted to pavements. The intent is to still achieve a "good" return on its bridge investments by holding their condition steady at the current good level while also improving the "returns" from the pavement investments.

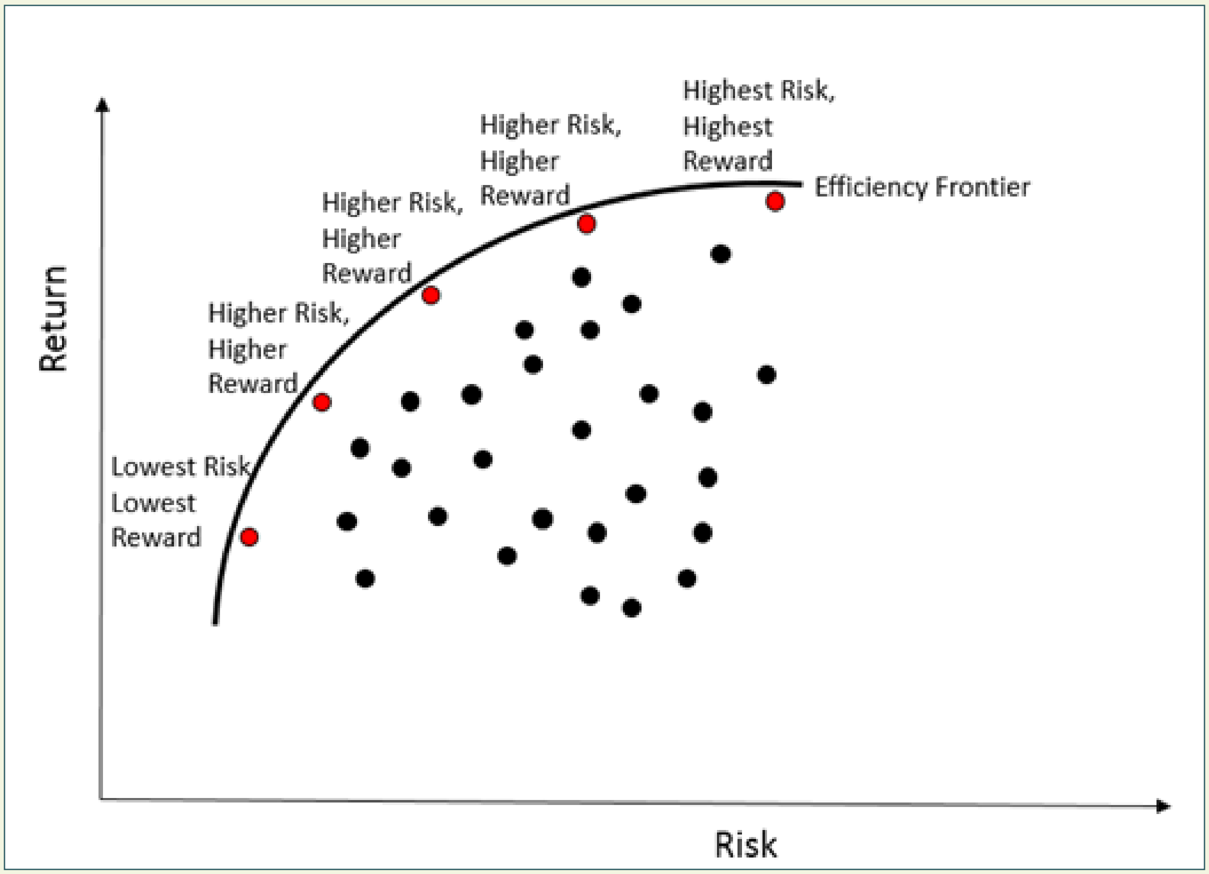

Figure 4. The Efficiency Frontier represents the highest possible return for a given level or risk.

In a cross-asset allocation exercise, the agency would not just consider the first, most obvious tradeoff between pavement and bridge. It would develop several bridge scenarios such as the one it adopted for targeting timber bridges and emphasizing preservation of good bridges. A second, risker, scenario would be to cut more money from the bridge program and slow the pace of timber bridge replacement. This second scenario would provide more money for pavements but also incur more risk that a timber bridge could fail. A third, even risker scenario, would be to also reduce the amount of bridge preservation. Again, this third scenario would produce even more pavement funds but also would increase the risk that in the future the department will see increased bridge degradation and higher future costs. So, the agency has three bridge scenarios. Each produces different amounts of revenue that could be transferred to pavements but all three scenarios produce different levels of risk.

In a risk/reward exercise, the agency would look beyond pavements and bridges and make similar tradeoffs of return and risk in programs such as safety or mobility. The agency would develop risk-based scenarios and seek to maximize its overall return for the risk it is willing to accept. The "return" the agency seeks to achieve would be measured by the degree to which it achieves its performance targets for asset condition, safety, mobility, and other objectives balanced against the risks it must take. The tradeoffs between programs or asset classes would be based on the agency officials' comparison of how each investment level would achieve its performance targets or asset conditions. The officials would document their decisions of the tradeoffs they make by accepting some lower performance outcomes as a result of shifting funds from one program to achieve higher outcomes in another program or asset class. The results are quantified in that each investment scenario includes costs and performance tradeoffs. The final decisions are made based on the executives' judgment of how the different investment levels maximize performance. In the investing world, this is sometimes referred to as "naive" allocation as opposed to optimized allocation. Optimized allocation would take the analysis further by using optimization software to compare costs and benefits of each option. The investing literature provides different opinions as to the degree to which naive investing under-performs optimized investing. The success of optimized investing depends upon the accuracy of optimization models. Similar issues are discussed in Cross-Asset Optimization section.

Quantifying or Monetizing Risk

Although risk is emphasized in the risk/reward allocation, risk could be included in both BCA and MCDA. Analysts in the insurance and finance world quantify or monetize risk routinely and then add it as a component to decision making. The same could occur with transportation agency investment decisions. A simple example is as follows:

To "save" money an agency decreases bridge preservation investments on 1,000 bridges which reduces long-term bridge performance in order to increase short-term spending on new highway capacity. To monetize or quantify risk the agency would estimate the percentage increase in probability that decreased bridge preservation will lead to higher costs. It multiplies that probability in a given year by the estimated cost to produce a risk value. For example:

Estimated annual probability that a bridge component will fail because of deferred maintenance = **0.01 or 1 percent.**

Estimate cost if the bridge component fails = **$250,000**

Risk "cost" is .01 × $250,000 or $2500 per component × 1000 bridges = **$2.5 million.**

In other words, the agency is taking on $2.5 million of risk each year that it defers preservation of 1,000 bridges. It could increase the 1 percent annual failure probability over time to reflect the effects of deferred preservation over more years and calculate the total cost of the risk over the horizon of the analysis.

This example is greatly simplified but illustrates how the intangible concept of risk can be quantified or monetized. More sophisticated versions of risk calculation are used by Wall Street and insurance companies to price risk, which then is the basis for "hedging" or otherwise mitigating risk in a portfolio. The underlying concept is that uncertainty or risk is real, it can impede achieving objectives and that it can be factored into decision making.

Cross-Asset Optimization

Cross-asset optimization represents a further refinement of cross-asset allocation. Cross-asset optimization is defined as "the use of recursive mathematical computations to determine the maximum utility for a given set of investments constrained by defined performance parameters." Optimization, therefore, is differentiated from cross-asset tradeoff or cross-asset allocation by its use of optimization routines and utility functions to develop an optimum investment mix. In the cross-asset tradeoff analysis, executives determined the tradeoffs "in their head" or in other relatively informal ways. In the cross-asset allocation, the executives made their tradeoff decisions by comparing costs and benefits, multiple criteria, or risk and reward. With optimization, they are computing a mathematical result using software that calculates hundreds or thousands of possible options and selects the one with the highest utility function.

The use of an optimization software routine to prioritize tradeoffs between asset classes or between projects or programs of projects therefore produces more sophisticated and quantified results but requires extensive data about attributes of each project, or program of projects.

The greater sophistication and complication is noted in the research project National Cooperative Highway Research Program Report 806 *Guide to Cross-Asset Resource Allocation and the Impact on Transportation System Performance.* NCHRP 806 produced an Excel-based prototype tool allowing users to set weights for the criteria of pavement smoothness as measured by the international roughness index (IRI), pavement overall condition rating (OCI), bridge overall condition rating (OCI), number of jobs created, number of crashes, and level of service and congestion. Once those values are known for different projects or for programs of projects, the software tool can calculate an optimized list of projects based on costs and values inputted in the Excel tool.

The report concluded that the framework and tool demonstrates that a cross-allocation approach to investment decision making across multiple assets can be developed. It says the prototype provides a framework that can be used to link planning, resource allocation, and programming to achieve performance goals.

The challenges include a lack of suitable candidate projects with adequate information on project details and anticipated performance impacts. More work is needed at the agency level to better understand how and where data must be aggregated to feed the tool. If an agency has hundreds of projects under development, the performance on each would be daunting to produce. Also, additional work is needed to include quality-of-life and other qualitative considerations into the tradeoffs. Another challenge is how to integrate the tool with existing management systems. Preferably, pavement, bridge, and other management systems would provide outputs that feed into the decision-support and optimization tool. Further challenges are how to include for consideration constraints such as the need for geographic equity across the state, environmental justice issues and the lack of flexibility among some funds.

Despite those challenges the tool demonstrates an advancement in optimization applied to transportation asset management, planning and programming. The type of optimized ranking demonstrated by the tool would be similar to some best practices in the fields of logistics, investment, or manufacturing. In those fields, investors expect decision makers to quantify their tradeoffs before making major investments. Such tradeoffs are less common in public infrastructure agencies, therefore, the tool demonstrates an early example of applying optimization to transportation agency investment decisions.

Two agencies, the Utah Department of Transportation and the New York State Department of Transportation, have either completed or are in process of optimization exercises. Officials from both agencies reported the exercises to be useful and to have improved their tradeoff analysis. One of the key benefits derives not from the technology per se but from the systematic effort needed to clarify the agency's objectives and how those objectives translate into selection criteria and weights. They said the tradeoff analysis improves the transparency of their decision making by leaving a clear record of what objectives were sought and the degree to which the options satisfied those objectives. One said that although software should not drive the asset management results, the optimization process and conversations that are required to develop inputs and priorities were very beneficial. Through these efforts, leadership is able to develop prioritization metrics that are used in cross asset evaluation and selection.

Conclusion

It is widely discussed among asset management advocates that documenting investment tradeoffs is important. Transparency in tradeoffs can build agency credibility and demonstrate how priorities and performance objectives drive decision making. Agencies can use a hierarchy of increasingly sophisticated decision methods to make and document their asset management decisions. The field of cross-asset tradeoffs, allocation, and optimization appear to be an emerging area of practice that can assist decision makers. As these practices become more widespread it is likely that users will want to develop common definitions and practices that mark the maturation of the discipline. It is the hope that this paper will advance understanding of tradeoffs, allocation, and optimization by suggesting common definitions that will enhance discussion of these methods.

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