Quantifying Performance Risks and Enabling Process Improvement in Transportation Asset Management

Larry Redd, P.E. – Corresponding Author
Redd Engineering
5302 Golden Willow Dr.
Fort Collins, CO 80528
www.larryreddLLC.com
Voice 970-219-4732
larryreddLLC@gmail.com

William Johnson
Performance and Asset Management Branch Manager
Colorado Department of Transportation
4201 E. Arkansas Avenue
Denver, CO 80222
Voice 307-512-4808
will.johnson@state.co.us

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Abstract

Various sources of uncertainty, variability, and volatility affect a transportation agency’s ability to perform. These sources of uncertainty include project costs, available revenue, project formulation processes, and performance modeling methods. These risks and uncertainties create overall variability in future outcomes and, similar to the manufacturing world, variability is a major cause of unwanted cost and bad performance.

In the transportation world, added costs may come from results such as delayed projects which can stem from variable project cost estimates or uncertainty in available revenue. Other added costs may result from poorly bundled projects developed from inconsistent processes and procedures. Finally, if performance modeling capabilities are not accurate or consistent then the inability to reliably forecast performance creates challenges in project planning.

In the spring of 2013, as an outcome of their internal assessment regarding asset and risk management capabilities, the Colorado Department of Transportation (CDOT) built a framework for strategically managing assets that includes the ability to manage performance risks. This framework involves the ability to predict performance, in order to look back in time to compare actual performance with the performance predicted years before. By 2014, CDOT was in full swing with this framework, by doing “plan versus actual” comparisons and analyzing the results.

By analyzing the variance between forecasted and actual performance, CDOT is now able to diagnose the root causes of disparities between projected and actual performance. With this knowledge it is possible to reduce variability, improve processes, adjust performance targets, and reach those targets more consistently.
INTRODUCTION

In an era of constrained resources, effective management of transportation assets is becoming an increasingly important function of transportation agencies. The Federal transportation reauthorization, Moving Ahead for Progress in the 21st Century Act (MAP-21), has further institutionalized asset management by requiring that all state departments of transportation (DOTs) develop a risk-based asset management plan for the National Highway System (NHS).

Even before the MAP-21 legislation was signed into law, the Colorado Department of Transportation (CDOT) had embraced asset management as an important business practice for maintaining its assets in a state of good repair over the long-term with the least investment of resources. For example, CDOT’s asset managers have been working with their various management systems since 2011 to develop budget scenarios and explore the relationships between funding and performance. CDOT has established risk-based asset management as the official approach for strategic preservation of the DOT’s assets and related investment decisions for those assets.

CDOT, as well as other transportation agencies are discovering the importance of assessing risks and identifying mitigating strategies. The need to consider risk-based opportunities along with performance-based investments in asset management decisions is becoming accepted practice. In addition, agencies are beginning to consider various levels of risk, including the corporate or “agency” level risks, as well as program and project level risks.

BACKGROUND

In early 2013, CDOT embarked on a project to formulate a transportation asset management plan, or TAMP. During that year, the first version of CDOT’s TAMP was drafted, refined, and published. At CDOT, asset classes beyond the MAP-21 requirements of Pavement and Bridges were covered in the TAMP; these asset classes included Maintenance, Buildings, ITS, Fleet, Tunnels, Culverts and Geohazards.

As part of formulating the TAMP a gap assessment was performed, which explored the TAM-related capabilities that might need further development. This assessment spanned five dimensions in evaluating the agency’s TAM capabilities, including:

1. Policy Guidance and Leadership
2. Planning and Programming
3. Program Delivery
4. Information and Analysis
5. Organizational

The result of this assessment indicated ten overall gaps for TAM, three of which are specifically related to risk (#2, #3, #4), as shown in the list below. Multiple others are strongly related to risk, such as #1, #5, #6, and #9.
1. Develop and document the current budget distribution, project selection and project tracking process
2. Integrate risk into planning and programming
3. Develop strategies to manage project and program delivery risks
4. Establish a risk framework to evaluate strategies
5. Analyze budget tradeoffs across programs
6. Improve project scoping and optimization
7. Incorporate life-cycle analysis into decision-making
8. Clarify the role of target setting
9. Implement a strategic management framework
10. Communicate benefits of TAM

Needless to say, the significance of risk in managing transportation assets became clear. A major effort was begun to establish how overall risk management would be approached at CDOT. A key part of this effort was to identify and characterize risks across the department, and for multiple levels such as agency, program, and project-level risks. This effort began by developing a risk register that would be included in the original Risk-Based Asset Management Plan (RB AMP) that CDOT was planning to finalize in late 2013 (1).

An excerpt of the CDOT Risk Register is shown in Table 1 below. Filling out the Risk Register began by identifying potential risk events, and then assembling a set of information regarding each risk. This included noting the level of risk, such as agency, program, or project level. In addition, the corresponding asset class was also noted. The scoring was done for all identified risk event types by estimating the probability of occurrence as well as the anticipated impact, should these events occur. Impacts were largely measured in terms of Safety, Mobility, Asset Damage, and Other Financial Impacts (e.g. community, overall economy, etc.) as illustrated in this excerpt of the Risk Register.

Lastly, risk management strategies were determined for each identified risk, including their benefits in terms of risk reduction, and their costs of implementation. Please note, however, that the context of the Risk Register was statewide, and the candidate risk management strategies listed in the Register were only general in nature and did not apply to specific situations. Hence the Risk Register was limited in its capabilities to support detailed decisions.
Following the initial draft of a risk register and the release of the first RB AMP, it was decided to continue to further develop the register. A major part of this effort was to further refine the various types of risks that CDOT faces and to better define the proposed management strategies for each risk event type, along with a more rigorous quantification of mitigation costs and benefits. Part of this refinement was to consider more than one management strategy, if feasible, rather than just considering a single strategy for each risk.

The updated Risk Register considered over 100 risks, and the risk scores associated with these risks are shown in Figure 1. Note that the majority of risk to CDOT resides in the top 50 or so risks. This information was very useful later in prioritizing risks to focus on.
Another result from the Risk Register was a breakout of risks by affected asset class, as shown in the bar chart in Figure 2. This information was very useful in the further analysis of risk. For example, one can see that several of these classes of risk have a geographic component. CDOT and researchers have addressed these types of risks in subsequent studies (2, 3 and 4).
In particular, the collection of "Agency" risks identified in the Risk Register needed to be further dissected, with the understanding that these types of risks were typically not geographically-related risks, but were risks that were related to the agency at the corporate level.

For example, various sources of uncertainty, variability, and volatility affect a transportation agency’s ability to perform. As shown here in Figure 3, these sources of uncertainty include project costs, available revenue, project formulation processes, and performance modeling methods. These sources of uncertainty create overall variability in future outcomes and, similar to the manufacturing world, variability is a major cause of unwanted cost and bad performance.

These types of risk largely affect overall system performance and whether projects are delivered on time, on budget, and as intended, thus delivering the targeted performance (5). It is these types of uncertainties regarding overall agency performance that are the subject of this research and others’ research (6).

![FIGURE 3 Example Histograms of Performance-Related Uncertainties](image)

Specifically, in the transportation world, added costs may come from results such as delayed projects which could stem from uncertain project costs or available revenue variability. Other added costs may result from poorly bundled projects, developed using inconsistent processes and procedures. Finally, if modeling capabilities are not accurate and consistent, then the inability to reliably forecast performance creates challenges in project planning.

Suspecting that significant savings were possible, a concerted effort was launched to examine the relevant performance-related uncertainties (cost variations, available revenue variability, inconsistent modeling, TAM processes, leadership and politics, etc.), and to determine how to manage them. A framework for strategically managing CDOT’s assets and
risks, as well as the necessary processes and data requirements were defined. It was hoped this approach would not only reduce performance-related risks at CDOT, but as a result improve overall performance, reduce costs, and enable continuous process improvement in asset management.

**STUDY OVERVIEW**

In late 2013, as an outcome of their internal assessment regarding asset and risk management capabilities, the Colorado Department of Transportation (CDOT) decided to build a framework for strategically managing assets that included the ability to manage performance risks. This framework would include the ability to look back in time to compare actual performance with the performance predicted years before. By 2014, CDOT was in full swing with this framework, doing Plan versus Actual comparisons and analyzing the results.

By analyzing the variance between forecasted and actual performance, CDOT is now able to explore the root causes of disparities between projected and actual performance. With this knowledge, it is possible for the agency to reduce variability, improve processes, adjust performance targets, and reach those targets more consistently.

Hence, the focus of this study was to provide an approach to dealing with the risks and uncertainties discussed above. The result of the research includes a strategic management framework for Transportation Asset Management (TAM) at CDOT in general. The research also recommends CDOT implement the framework for Pavements with an associated process. By implementing a comprehensive “Plan, Do, Check, Act” management framework, CDOT:

- Established leading and lagging indicators for performance measures, for use in performing a “Plan versus Actual” analysis between these indicators and the original plans and projections.
- Established the time horizons (4 and 8 years) for conducting the Plan versus Actual analysis
- Is now able to implement causal analysis and process improvement efforts related to any “gaps” between:
  - Recommended work treatments and the subsequent projects delivered, and
  - Anticipated (projected) asset performance and actual performance.

Eventual causal analysis will help quantify the influences that drive these gaps, and will better inform the choices of mitigating actions, leading to continued process improvements over time.

**MAJOR STEPS IN THE STUDY**

In order to accomplish the objectives of strategically managing performance risks and assets in general, CDOT first needed to implement a “Plan, Do, Check, Act” framework. Implementing this framework has now enabled CDOT to monitor the desired measurements, i.e. Leading and Lagging indicators, and to conduct causal gap analysis and make process improvements on a continuous basis that will help the agency:
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− Close the gaps between anticipated performance and actual performance;
− Achieve long-term performance that corresponds to established, strategic targets; and
− Provide sustainability of the overall TAM approach, with sound, repeatable processes

**Defining the “Plan, Do, Check, Act” Framework**

The anticipated strategic management framework was intended to help CDOT utilize and coordinate all of the various elements of TAM. Thus in developing the RB AMP, CDOT chose a “Plan, Do, Check, Act” approach as the organizing framework for asset management. This framework is illustrated in Figure 4 and described below.

**FIGURE 4 TAM Strategic Management Framework**

**Plan, Do, Check, Act**

- **Plan** – The “Plan” phase focuses on defining an optimized set of projects and determining when they should be scheduled for delivery. CDOT’s Asset Investment Management System (AIMS) provides decision-makers with performance information based on various levels of funding for each program. This allows CDOT to tradeoff various investment levels across assets, and make funding distributions. CDOT’s Financial Plan then defines budgets per asset, by year. Once a budget has been defined, specific projects are selected.

- **Do** – The “Do” phase is where projects are programmed, designed, and built. This phase begins by updating the State Transportation Improvement Program (STIP). A major
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- **Objective during the “Do” phase**: The objective during the “Do” phase is to minimize the risks of project delivery and strive to deliver projects on time and as originally intended.

- **Check**: The “Check” phase focuses on gathering and examining “feedback” on a continuous basis. This phase tracks the health of the network and determines how well previous plans have worked. The effort is based on information provided by the asset managers and regions, and enables a better understanding of the cause-and-effect between investments and results, including the feasibility of the latest set of performance targets. This understanding enables the agency to adjust its targets and strategies for the future. Ultimately, this insight will result in increased effectiveness throughout the overall process and increased confidence in decision-making, leading to continuous improvement.

- **Act**: Information from the “Check” phase feeds into the “Act” phase, where CDOT determines its strategic priorities and sets new strategic directions based on strategic and statewide plans and a thorough analysis of performance trends relative to targets. This phase involves evaluating the gap between the desired function of future infrastructure and anticipated funding, and identifying the gaps between actual performance and previously projected performance. During this phase, a full-blown causal analysis of these gaps may eventually be performed. This gap analysis will enable CDOT to better adjust targets and focus available resources in the “Plan” phase. During the “Act” phase, decision-makers also assure that performance metrics are linked directly to stated goals of the department.

The “Plan, Do, Check, Act” process has been implemented successfully by numerous private- and public-sector agencies seeking to improve their management and decision-making processes. Arie De Geus, the former Head of Planning for Royal Dutch/Shell, once said, “The only sustainable advantage an organization has is in its ability to self-scrutinize.” Hence, the feedback of information, the self-scrutiny, and the learning that this framework will provide to CDOT will assure the highest possible level of asset management success and sustainability.

**Details of the Research -- Recommendations for Implementing the Framework**

The following provides the research and analysis details behind the approach CDOT is taking in implementing the “Plan, Do, Check, Act” framework. Early-on, a decision was made to implement the framework for the Pavement program where CDOT had already implemented many elements of the framework. The following recommendations focus on the “Check” and “Act” steps in the framework, which were the biggest needs for pavements in the framework. For Pavement, the gap analysis for asset condition involved comparing the actual drivability life (DL) over time with the projected performance. Specifically, the “gap” is defined as the differences in actual performance from the Plan (i.e. the predicted conditions), over a range of time horizons. For example, CDOT could measure DL at 1 year, 4 years, or 8 years
following the predictions of DL conditions. DL should be tracked for Interstates, CDOT-Owned NHS, and the State Highway System, per the measures outlined in Table 4.1 in the RB AMP.

To determine what drives the “gaps” in performance between “planned” surface treatments (predictions) and actual pavement performance results, it was necessary to understand the current practices at CDOT regarding predicted performance and the information used in making these predictions. Recommended treatments may vary from those that are actually implemented.

Currently CDOT measures this variance in a leading indicator that measures the percent of recommended projects that get done. The current target is that 80 percent of recommended projects/treatments are implemented. Any variation from 100 percent of recommended treatments (resulting from the predictive analysis) would result in at least some influence on the gap in predicted versus actual performance, especially in longer-term time horizons.

According to current practice, the actual treatments that are implemented are input into the Pavement Management System (PMS) analysis in order to complete the details of project history within the PMS. CDOT includes these “committed projects”, which are intended over the next four years, in the predictive analysis in order to tighten the predictions. CDOT replaces “recommended treatments” in its PMS analysis with “committed projects”, because there can be up to a 20 percent difference between the two lists. Since CDOT implements most of its “committed projects”, it is anticipated that this approach will enable CDOT to limit the influence of project discrepancies on the DL performance gap for the first four years.

Therefore, the 20 percent flexibility in projects (which is based on the 80 percent match requirement) is largely minimized as a gap driver for gap analyses with time horizons of four years or less. For those time horizons, this leaves the funding variations from “planned” as the major gap driver (in theory) along with any inaccuracies in the predictive modeling capabilities. Nonetheless, the influences of all these contributors to the “gap” need to be analyzed.

For gap analysis time horizons longer than four years, there are unknown differences between recommended treatments and the actual treatments that will apply. For these time horizons, the 80 percent match requirement tends to provide a constraint on these unknown differences. However, since the actual anticipated projects are not yet known to the PMS analysis, and all “recommended” treatments are the basis of the predictions beyond four years out, the 20 percent flexibility is a first order gap influence in time horizons greater than four years. In other words, the 20 percent is a wild card that should be part of the gap analysis in order to explore the types of uncertainties mentioned here.

**Time Horizons Used in the Gap Analysis**

Setting up the framework for gap analysis requires a well-informed choice of time horizons. For example, predicted performance within a 4 year time horizon at CDOT should have less sizeable gaps between planned and actual performance relative to a longer time horizon. Specifically, beyond the first four years, predictions will suffer from the number of non-recommended projects being implemented. This effect, combined with the inherent
challenges of making predictions several years into the future, provides understandable,
explainable reasons for greater divergence between “planned” and “actual” performance beyond
four years. Skilled and informed causal analysis will be most straightforward and successful if
time horizons are chosen properly. Rationale such as that developed in the above analysis is
necessary for making sure time horizons are well understood, and not simply chosen arbitrarily.
Note: the rationale and conclusions for choosing time horizons may vary from agency to agency.

Figure 5 provides potential gap influences by time horizon. While CDOT could institute
Lagging Measures at the 4 year time horizon, in addition to the 1 year time horizon used in their
Deficit Report, a longer-term time horizon would also provide valuable insight, even with the
divergent aspects in predictability. Actually, the insight would be valuable because of the
divergent aspects in predictability. These longer-range indicators, for example, would provide
some visibility regarding the importance of the 80 percent “Leading Indicator” (i.e. regarding the
“match” between recommended and implemented treatments). A reasonable conclusion here,
then, would be to perform gap measurements at the 8 mark; because of the additional four years
from the first four year horizon. Note: The 10 year mark is commensurate with the fiscal
constraint time horizon of 10 years; so either 8 or 10 years would be a valuable time horizon.

<table>
<thead>
<tr>
<th>Gap Amount</th>
<th>Prediction Date</th>
<th>Prediction Time Horizon -- Years</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gap Influences – up to four yrs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Funding variations from the inputs to “predictive analysis” -- Major</td>
<td>+4</td>
<td></td>
</tr>
<tr>
<td>2. Modeling inaccuracies -- Minor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. “Committed projects” that do not get completed as intended -- Minor</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Gap Influences – past four yrs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Funding variations from the inputs to “predictive analysis” -- Major</td>
<td>+8</td>
<td></td>
</tr>
<tr>
<td>2. Modeling inaccuracies -- Major</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. The “20% Wiggle Room” in the Match Indicator -- Medium</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**FIGURE 5** Gap Influences by Time Horizon

**Gap Analysis Overview**

The general concept of gap analysis is shown in Figure 6. The targets represent the
objectives of “zeroing in” on anticipated performance targets (i.e. the “bulls eyes”), as well as
having a tight tolerance or “pattern” around the target. Examples of potential uncertainty
parameters are listed beside each target, to illustrate how variations in the parameters can affect
whether the targets are being met. Note: The “target” in this example is representative of a performance objective for most any asset type, framed in fairly general terminology.

\[ \text{FIGURE 6 } \text{Example Root Cause Analysis for Converting “Plan versus Actual” Results to Process Improvement Rationale} \]

Information from the gap analysis can help improve PMS analysis predictive capabilities by feeding back to the analysis findings on how the models may be affecting the gaps. Specifically, the modeling parameters in the Pavement analysis (constant factors, equation formulations, treatment costs per sq. yd., etc.) will affect the gaps being measured. A better understanding of the variations in other gap influences (planned versus actual revenues, etc.) may be helpful in sorting out modeling influences versus other influences on the gaps.

Gap analysis related to modeling is currently performed on an on-going basis by the Pavement Management Branch, primarily due to their experience and tacit understanding of the modeling aspects of making predictions. In their analysis, the general “drivers” of modeling-related gaps are noted, along with the percentage of the overall gap that is due to modeling, assuming this is discernable. This feedback is then factored back into the modeling approach.

\[ \text{RESULTS AND CONCLUSIONS} \]

The above framework and processes have been put into place at CDOT for strategically managing assets, including the management of performance risks. CDOT is now able to set or re-set targets based upon growing knowledge of how various factors affect performance outcomes. In addition, variability can now be reduced on an on-going basis, due to the new
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capability to “close the loop” on the “Plan, Do, Check, Act” cycle. This will allow CDOT to reduce costs, improve performance, and work toward continuous improvement over time. The work done to date is within the context of pavement-related investments, and the processes involved with this approach have been verified for use with other asset classes.

**Future Efforts**

CDOT is beginning to apply the “Plan, Do, Check, Act” framework for Pavement, as described above. CDOT intends to develop similar approaches for Bridge and Maintenance and, over time, expand into additional asset classes. In addition, it is anticipated that the Monte Carlo approach shown in Figure 7 would be extremely useful in making performance projections. By combining the anticipated variations of the various input parameters into performance projections, even more can be learned by actually modeling uncertainty in the projections.

Variations in Input Values
(Uncertainty Factors)

![Monte Carlo Analysis](image)

**FIGURE 7  Monte Carlo Analysis Utilized in Making Performance Projections**

Further, with a few years of “Plan versus Actual” analysis experience, Monte Carlo analysis may reap even more significant learning, and hence enable even greater process improvement. By performing scenario analysis to explore the root causes of parameter variations and projected results, the ability to zero in on causes and effects will be accelerated. Finally, it is anticipated that this approach will be compared with other works as a means of validating the approach and imbedded processes (*7, 8, 9, and 10*).
Detailed Steps for Implementing the Framework

1. Identify the Asset’s Leading Indicators.
2. Identify the Asset’s Lagging Indicators.
3. Perform the gap analysis:
   a. Choose time horizon(s) for measuring gaps.
   b. Annually compare projected performance with the actual performance for each time horizon(s). For example, in 2020 compare the actual performance or condition of the asset in that year with the projected 4 year performance from 2016.
   c. Identify the “gaps” between projected and actual performance for each time horizon.
   d. Quantify the gaps.
   a. Causal analysis of the gaps: employ one or more of the following techniques:
      i. Root Cause Analysis (RCA); Ishikawa Diagramming
      ii. Kepner-Tregoe: Potential Problem Analysis; or
   b. Results of the causal analysis:
      i. Identify the linkages between potential causes and the impacts (Gaps).
      ii. Determine the causes with the highest impact(s) and leverage.
      iii. Compare with the results from the previous plan vs. actual analyses.
5. Determine process improvements, based upon the most sensitive impacts to performance that are process related.
6. Implement process improvements.
7. Track the improvements in the gaps.
8. After the annual root cause analysis and process improvement implementation, consider any impacts on the following, and whether any adjustments need to be made:
   a. Do the results of the causal analysis inform better long-range planning?
   b. Consider adjusting performance targets.
   c. Consider adjusting the cross-asset optimization process.
9. Consider any changes to leading and lagging indicators.
10. Repeat this effort annually.
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