Transportation Association of Canada

Performance-Based Decision Making for Asset Management: Lessons Learned and Practitioner Toolkit

October 2021

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ISBN # 978-1-55187-710-5

TAC report documentation form

Title and Subtitle
Performance-Based Decision Making for Asset Management: Lessons Learned and Practitioner Toolkit

Report Date	Coordinating Agency and Address	ITRD No.
October 2021	Transportation Association of Canada 401-1111 Prince of Wales Drive Ottawa, ON Canada K2C 3T2	

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Abstract
Governments, including transportation agencies, are increasingly adopting performance-based approaches to management and decision making to help achieve desired outcomes, and to encourage fiscal responsibility, accountability and transparency in governance.

As financial resources become more limited and governments focus on obtaining value for money, transportation agencies are increasingly required to make investments using cross-asset trade-offs and optimization methods to improve transparency and credibility using a performance-based approach to decision making.

Despite recent progress, there is still much to learn about performance-based decision making and the best techniques to ensure success. Many public transportation agencies seek practical examples and tools that could be deployed to advance their asset management practices, improve the transparency of decision making, and optimize network investments. This report helps close that knowledge gap by synthesizing lessons learned with respect to performance-based decision making, and by developing a toolkit that can help practitioners identify tools to implement for different needs within the asset management process.

Keywords
Economics and Administration

- Performance indicator
- Decision process
- Asset management
- Pavement management system
- Bridge management system
- Textbook

Additional Information:
Recommended citation: Montufar, J., Regehr, J., Chapman, S. and Haas, R. 2021. *Performance-Based Decision Making for Asset Management: Lessons Learned and Practitioner Toolkit.* Ottawa, ON: Transportation Association of Canada.

Acknowledgements

Project Funding Partners

- Autorité régionale de transport métropolitain
- British Columbia Ministry of Transportation and Infrastructure
- Manitoba Infrastructure
- Metrolinx
- Ministère des Transports du Québec
- Ministry of Transportation, Ontario
- New Brunswick Transportation and Infrastructure
- Ontario Goods Roads Association
- Saskatchewan Ministry of Highways
- Transport Canada
- Ville de Montréal

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In memoriam

Dr. Ralph Haas passed away unexpectedly prior to the publication of this report. As a co-author, Dr. Haas made valuable and significant contributions to the research that formed the foundation of this report. His pioneering work in pavement engineering and asset management, some of which is reflected in this report, advanced asset management practice across Canada and in other countries.

Among the many honours and distinctions he earned throughout his life, Dr. Haas was Distinguished Professor Emeritus in the Department of Civil Engineering at the University of Waterloo; a member of the Order of Canada, the Royal Society of Canada, and the Engineering Institute of Canada; and a fellow of the Canadian Academy of Engineering.

A proud engineer, wise academic, prolific author, and world-renowned expert in pavement design and asset management, Dr. Haas was also a distinguished, decorated and dedicated Honorary Life Member of TAC. He served as an active volunteer on numerous councils and committees for over five decades.

Dr. Haas was passionately committed to giving back to his country and profession. He was one of the founding members of the TAC Foundation, which supports the education and training of tomorrow's transportation professionals. He gave not only his time and expertise, but was extraordinarily generous in the personal donations he made to the foundation over many years.

As his co-authors, we hope this report builds on this legacy; we are truly honoured to have worked alongside Dr. Haas on this project.

Executive summary

Governments, including transportation agencies, are increasingly adopting performance-based approaches to management and decision making to help achieve desired outcomes, and to encourage fiscal responsibility, accountability and transparency in governance.

As financial resources become more limited and governments focus on obtaining value for money, transportation agencies are increasingly required to make investments using cross-asset trade-offs and optimization methods to improve transparency and credibility using a performance-based decision-making approach. Despite recent progress, there is still much to learn about performance-based decision making and the best techniques to ensure success. Many transportation agencies seek practical examples and tools that could be deployed to advance their asset management practices, improve the transparency of decision making, and optimize network investments. This report helps close that knowledge gap by synthesizing lessons learned with respect to performance-based decision making, and by developing a toolkit that can help practitioners identify tools to implement for different needs within the asset management process.

This study had three major objectives:

- To synthesize practice in performance-based evaluation, optimization and decision-making processes and techniques
- To identify lessons learned and provide recommendations and considerations for public agencies to improve evaluation and decision-making processes
- To provide practical tools for agencies to share and improve evaluation processes and techniques

The study involved five major tasks:

- A comprehensive review of more than 100 national and international publications on performance-based decision making
- An extensive online survey of TAC member agencies to obtain information regarding each agency's asset management program, with 53 responses received from across Canada
- Telephone interviews with 15 agencies, which were selected from the responses to the online survey
- Case studies to illustrate applications of performance-based decision processes and optimization methods involving: (1) cross-asset optimization; (2) development and implementation of a performance-based asset management program; (3) resource allocation within a transit agency; and (4) pavement management
- A visioning workshop to identify tools for inclusion in the practitioner toolkit

Performance-based decision making

Performance management is defined in the literature as "the practice of setting goals and objectives; an on-going process of selecting measures, setting targets, and using measures in decision making to achieve desired performance outcomes; and reporting results" (Grant et al., 2013).

Public transportation agencies have implemented performance management principles into their planning and programming processes in order to:

- Improve program and project delivery with respect to desired performance outcomes
- Support decision making as it pertains to funding allocation and investments
- Provide transparency and accountability to the public
- Comply with good governance practices

The implementation of performance-based decision making starts with the elements of high-level strategic direction and planning analysis. These elements contribute to programming decisions, which interact with implementation and evaluation activities. The outcomes of ongoing monitoring and evaluation feedback into refined strategies and plans, creating a management cycle that guides decision making over time. Quantitative and qualitative data fundamentally underpin all elements of performance-based decision making. Therefore, there needs to be an emphasis on the collection of good data for monitoring, analysis and decision making.

Performance measures may be classified as inputs, outputs and outcomes. *Input measures* reflect the resources available within an agency to carry out a task. *Output measures* reflect the way resources are used, the scale or scope of activities performed, and the efficiency of converting allocated resources into a product. *Outcome measures* reflect the degree of success of the agency in achieving its goals and objectives. While the literature emphasizes the need for increased utilization of outcome measures, agencies suggest that a blend of output and outcome measures should be considered.

When selecting performance measures, consideration should be given to the following requirements: measurability, forecastability, clarity, usefulness, relevance, multimodality, temporal effects and geographic scale. At a high level, common categories for measuring transportation system performance include: safety, system preservation, system operations, quality or level of service, reliability, connectivity, accessibility, freight mobility, economic vitality, environmental sustainability, energy security, livability, resilience and organizational excellence. Given that an agency's selected performance measures determine the types of projects that get prioritized, it is important that these measures relate to its goals and objectives.

The literature consistently cites the benefits of implementing performance-based decision making for transportation agencies and the stakeholders they serve. However, despite these benefits, challenges have emerged as performance management approaches have matured, particularly as they become more sophisticated in their use of data and tools, more comprehensive in their application across modes and asset classes, and more capable of addressing competing objectives within an agency.

In Canadian jurisdictions, system preservation (i.e. asset management) is the most advanced and mature application of performance measures.

Asset management and performance-based decision making

The underlying goal of asset management is to provide greater value to the system and a good level of service for end users through improvements in program effectiveness and system performance. This can be achieved by maintaining a comprehensive asset inventory; up-to-date condition measurement; analytical tools to forecast changes in condition, service, or performance over time; treatment guidelines; and models to estimate treatment costs, implications and effectiveness.

As budgets become increasingly limited, robust asset management coupled with meaningful financial reporting is essential for efficiently and effectively maintaining infrastructure systems. However, despite the critical link between performance-based asset management and financial decision making, not all agencies successfully link these administrative processes. In fact, commonly cited issues that work as barriers to implementing a performance-based asset management program involve leadership, administrative and institutional issues. These barriers have been found to arise because of the functional segregation of many agencies, a lack of consistent senior leadership, unpredictable funding, competing objectives within the organization, political influences, and external mandates for establishing benchmarks and reporting performance. Engaged leadership, an agency-wide commitment to knowledge management, and the adoption of technically sound and data-driven practices have been found to help address these challenges.

As asset management programs mature, issues involving priority setting between program elements have emerged. Such issues can span across modes and/or asset classes. This has resulted in the need for consistent definition and application of outcome measures to successfully link system performance with project programming.

In recent years, the focus of asset management has shifted toward achieving a sustainable system. This creates the need for asset management practices to align with broad economic, social and environmental objectives. Further, there is a recognition that sustainability, as it relates to asset management, involves proactive consideration of current and future user demands for highway infrastructure and responsible adoption of demand-responsive policies and technologies.

Effective implementation of performance-based decision making relies on the availability of good data. The literature emphasizes the importance of developing agency-wide data governance strategies, the appointment of data stewards, and the implementation of flexible data warehousing systems to help increase the robustness of an asset management program.

Optimization methods in asset management

The allocation of limited resources within an agency requires technical tools and sound judgement by a range of decision makers. While many potential methods and techniques are available for optimization of resource allocation, existing tools are not well suited for guiding practical decision-making processes which cross the boundaries of asset type (e.g. pavement versus bridge), mode (e.g. highway versus transit), work class (e.g. maintenance, operations, construction), or objective (e.g. safety, preservation, mobility). Therefore, there are a wide range of considerations and challenges associated with the optimization of funds in asset management, and agencies must be cognizant of these issues when applying optimization methods that suit their unique goals and objectives.

Conventional decision-making methods used in asset management include engineering judgement and engineering economics tools such as present worth and cost-effectiveness.

The application of engineering economics principles to asset management has become common practice, despite limitations concerning discount rate uncertainties, monetization of certain types of costs and benefits, an inability to account for multiple stakeholder viewpoints, potential misalignment of economic analysis results with agency goals, and the need to integrate risk-based and probabilistic techniques. The literature refers to these types of tools as near-optimization tools. Other available optimization tools include risk assessment and risk management, multi-objective optimization, and trade-off analysis.

Other optimization tools include risk assessment and risk management, multi-objective or trade-off analysis, and cross-asset optimization.

While beneficial for asset management programs, the assessment and management of risks requires a significant level of effort and expertise, potentially disregards qualitative inputs in an increasingly quantitative type of analysis, and requires careful protocols for communicating risks to decision makers and other stakeholders.

With respect to cross-asset optimization, despite technical advances most current transportation asset management practices address resource allocation within a single asset class. Still, the potential for a more holistic approach has motivated agencies to seek structured cross-asset optimization approaches. Various multi-objective optimization methods have been successfully implemented by different agencies.

Implementation of performance-based decision making for asset management

Based on the survey of agencies, pavements were found to be the most common asset class for which most Canadian agencies have asset management programs in place, followed by bridges.

In general, when considering all types of asset management programs, the survey found that agencies are highly satisfied with their asset management programs as it pertains to data quantity, data quality, data completeness and data currency. Further, because pavement asset management programs have been in place longer than other types of programs, these programs show the highest satisfaction level with data quantity. Conversely, the lowest satisfaction levels of all asset management programs were identified for paths and sidewalks due to software capabilities, currency and staff turnover.

Intangible assets such as data and human capital are, for the most part, not included as part of agencies' asset management programs. However, for those agencies that do operate asset management programs for intangible assets, data was reported as being the most common intangible asset.

With respect to cross-asset optimization, the survey found that most agencies do not apply cross-asset optimization. For those that do, the most common combination of asset classes in cross-asset programs are as follows:

- Pavements and bridges
- Pavements and subsurface infrastructure
- Bridges and culverts
- Pavements and culverts
- Pavements and paths and sidewalks

With respect to resource allocation to transportation infrastructure asset management, the most commonly stated challenges identified by participating agencies are:

- Limited available staff time and contractor resources to develop, operate and maintain a program, as well as a limited budget and resources for required staffing
- Ensuring a robust and consistent understanding of all asset needs for maintenance, growth and expansion (i.e. creating an inventory of assets and assessment of conditions)
- Consistency and timely program delivery due to inadequate funding and staffing; delays in implementing preservation treatments for the right asset at the right time lead to accelerated deterioration that results in costlier treatments
- Complexity of technology and the need for expertise other than civil engineering
- Extreme weather and geotechnical (e.g. permafrost) condition
- A well-established cross-asset allocation method that optimizes investments across various asset classes in the whole transportation system
- Lack of best practice asset management for other assets besides pavements and structures (e.g. rest areas, truck inspection stations, ferry services, remote airports, illumination, guardrails, median barriers, traffic signals, signs, salt domes, patrol yards)
- Moving towards a more service-oriented asset management approach, versus the older traditional asset-centric model, that includes a multimodal and active/mass transportation perspective
- Institutional challenges such as the procurement process for software programs and changing plans for infrastructure investments
- Political pressures for other capital infrastructure
- Lack of leadership and understanding from senior decision makers regarding the value of an asset management program

Based on the three case studies conducted as part of this project, the following was found:

- Designing, developing and implementing a performance-based asset management program takes vision and good leadership, collaboration and commitment, which was also identified in the literature as key success elements.
- Data-driven change management is essential. The implementation of a proof of concept can allow for feedback throughout the process for continuous improvement. A data-driven approach can also help to demonstrate the value of good asset management practices.
- Investing in data collection and maintenance will greatly assist in supporting data-driven decisions. High quality data is perceived as being the most important asset in a robust asset management program, since infrastructure investment cannot happen without access to good quality data. To ensure an agency can successfully make the argument for the importance of data, evaluate the replacement value of the data owned and what the implications would be on the overall asset management process in the absence of that data.
- Important parameters that can be used to evaluate the business value within an asset management decision support system are: strategy and policy, customer experiences, stakeholder and reputation, business effectiveness, human resources, added safety and security, and added environmental benefits.
- The relative weights of all parameters used in decision making should be assessed annually to ensure corporate objectives are met.
- Stakeholder engagement is essential to ensure collaboration at all stages of the process. This results in increased trust and partnerships that ensure success.
- A strong public relations strategy is beneficial, particularly when engaging stakeholders.

- Providing specialized asset management training for staff can help with the success of a program. The goal is to always ensure that staff skills are up to date with best practices.
- Documentation of all processes that comprise the asset management program is essential; if the agency undergoes a reorganization, this permits a more successful and seamless transition with minimal interruption to the asset management program.

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1. Introduction

1.1 Study background and need

Governments and transportation agencies are increasingly adopting performance-based management and decision-making approaches to help achieve desired performance outcomes, and to encourage fiscal responsibility, accountability and transparency in governance. The motivation for adopting a performance-based approach is both internal and external. Internally, the approach enables an agency to make, monitor and evaluate decisions on policies and programs with a clear view of established goals. Externally, it allows comparisons between agencies in different jurisdictions and improves the transparency of decision making in the context of scarce resources and heightened public expectations about safety, level of service, infrastructure condition and sustainability.

Fundamentally, performance-based decision making involves the establishment of high-level goals and actionable objectives that contribute to those goals (Cambridge Systematics, 2000; Grant and Smith, 2013). Performance measures (or indicators) are devised to measure progress towards a goal and may be broadly categorized as inputs, outputs and outcomes. An input indicator reflects the resources available to carry out a task. An output indicator reflects the way resources are used, the scale or scope of activities performed, and the efficiency of converting allocated resources into a product. An outcome indicator demonstrates the degree of success of the agency in achieving its goals and objectives.

The ability to reliably measure performance indicators is critical to the success of performance-based decision making. Unfortunately, collecting and analyzing indicator data leads to a common pitfall, which is aptly captured by the well-known axiom: We manage what we measure. Too often, agencies inadvertently pursue and measure activities that do not align with established goals and objectives, and many times this occurs because input and output indicators are more easily measured and tracked than outcome indicators, but do not contribute to progress towards a goal.

Performance-based decision making is at the core of contemporary asset management practices. In Canada, annual investments in transportation infrastructure continue to fall short of needs, resulting in a persistent and growing backlog of maintenance and rehabilitation (sometimes referred to as the infrastructure deficit). This problem is pervasive and has emerged as a critical challenge given constrained budgets and increased demands for infrastructure use. Recognizing this challenge, considerable research and development have been directed to optimize the use of public funds for projects and programs that best contribute to an agency’s target outcomes. A key milestone has been the progression from the practice of managing assets (often within a single asset class) to the more holistic concept of asset management throughout an asset’s life cycle and across asset classes. This evolution has been formalized internationally through the *ISO 55000 Standards for Asset Management* (International Organization for Standardization, 2019).

Another important recognition has been that the provision of transportation infrastructure occurs to serve public demands. This has led to demand-oriented asset management policies that are more responsive to changing user needs (International Transport Forum, 2018). While a demand-oriented perspective is an important step forward, the approach raises numerous complexities about managing trade-offs between modes (e.g. prioritizing infrastructure for trucks or pedestrians), between different sub-networks or regions within a jurisdiction, and across asset classes.

Data-driven approaches to support asset management decision making, including various types of optimization and probabilistic methods, have enabled decision makers to leverage available information and consider uncertainties more explicitly within the decision process (Cambridge Systematics, 2005). These approaches rely on the analysis and integration of quantitative and qualitative data sets. In fact, the critical importance of data within performance-based decision-making processes has motivated many jurisdictions to adopt data governance practices that reflect the need to manage data as an asset unto itself (Gharaibeh et al., 2017).

As financial resources become more limited and governments focus on obtaining value for money, transportation agencies are increasingly required to make investments using cross-asset trade-offs and optimization methods to improve transparency and credibility using a performance-based decision-making approach. A key challenge is the lack of understanding regarding the implications of this type of approach. In addition, there is still much to learn about performance-based decision making and the best techniques to ensure success. Many transportation agencies seek practical examples and tools that could be deployed to advance their asset management practices, improve decision-making transparency, and optimize network investments. This report helps close that knowledge gap by synthesizing lessons learned with respect to performance-based decision making, and by developing a toolkit that can help practitioners identify tools to implement for different needs within the asset management process.

1.2 Study objectives

This study has the following objectives:

- To synthesize practice in performance-based evaluation, optimization and decision-making processes and techniques
- To identify lessons learned and provide recommendations and considerations for public agencies to improve evaluation and decision-making processes
- To provide practical tools for agencies to share and improve evaluation processes and techniques

The scope of the project includes the following topics:

- Performance-based decision processes, applications, key objectives and comparisons
- Experiences, outcomes and best practices in performance-based decision making
- Alternatives for improving performance-based optimization and decision making
- The need for performance-based tools for asset management and cross-asset allocations
- Challenges associated with resource allocation and optimization of investment funds
- Optimization methods used for asset management and evaluation of funding options, including examples, the evolution of methods for pavements and bridges, and effectiveness
- Level of service associated with resource allocation for different asset classes
- Best practices in establishing the duration of cross-asset life-cycle analysis
- Life cycle issues, sustainable development issues, operating and capital issues with consideration to different modes, priorities and investment types

1.3 Study methods

Literature review

A comprehensive review of national and international literature on performance-based decision making was conducted. The review addressed the following topics:

- *Performance-based decision making* – What is it? Why is it used? What does it entail? Who is using it? What are the key objectives of performance-based decision making?
- *Considerations within a performance-based decision-making framework* – These include life cycle issues, sustainable development issues, operating and capital issues, and priority setting between program elements
- *Optimization methods and techniques in asset management* – What techniques are available, and who is using those techniques? What is the rationale for implementing these techniques? How are these techniques characterized? Which techniques are applicable to pavements, bridges and other infrastructure? How have assets performed as agencies transitioned from "worst-first" asset management to an optimization method?
- *Cross-asset resource allocation analysis* – This includes historical practices, resource allocation approaches, decision models, and considerations for life cycle analysis

The literature review included engineering periodicals and journals; readily available papers and texts; conference proceedings; and academic, government and industry reports. The literature review identified over 150 publications that address the issues investigated in this project, and after further examination about 100 were deemed applicable.

Online survey

An extensive online survey of all TAC member agencies was conducted to obtain information regarding each agency's asset management program. Survey questions were distributed to all TAC member jurisdictions, and responses collected using interactive online survey software. Provinces, federal agencies, utilities, and transportation authorities or associations were the target audience. The final survey questionnaire is included in Appendix A.

The online survey received 53 complete responses: 24 from municipalities, 27 from provinces and territories, one from a federal organization, and one from a transportation association. Multiple responses from the same agency, but submitted by different respondents, were considered together. Table 1 lists the responding agencies.

Table 1: Agencies responding to the online survey

Municipality (19)	Airdrie, AB Brantford, ON Calgary, AB Charlottetown, PEI Courtenay, BC Greater Sudbury, ON Leamington, ON Leduc, AB Montréal, QC New Tecumseth, ON	Prince George, BC Regina, SK Saskatoon, SK Spruce Grove, AB St. John's, NL Toronto, ON Vaughan, ON Winnipeg, MB York Region, ON
Province/territory (10)	Alberta British Columbia Manitoba New Brunswick Northwest Territories	Nova Scotia Ontario Prince Edward Island Saskatchewan Yukon
Federal government (1)	Parks Canada	
Regional transportation authority (1)	TransLink	

Telephone interviews

Telephone interviews were conducted with 15 agencies (see Table 2) selected according to the following criteria:

- Those who responded to the online survey and indicated that they were satisfied with their asset management programs; emphasis was given to those who reported they managed multiple assets, implemented cross-asset optimization, or used a variety of optimization methodologies
- Those with members on the Project Steering Committee
- Those that represented a variety of population sizes and government agencies (i.e. municipalities, provinces, transit authorities)

The interviews were conducted in August 2019 and involved telephone discussions of up to one hour on the following topics:

- The agency's asset management program:
  - Overall structure and development
  - Assets managed (tangible and intangible assets)
  - Asset management tools (i.e. software programs or platforms)
- The program's performance-based management and decision-making framework:
  - Resource allocation methodologies
  - Tools that are highly beneficial to the agency for performance-based decision making
  - Cross-asset optimization processes

- Challenges and lessons learned:
  - Challenges experienced by the agency throughout the process of developing, implementing, and operating an asset management program
  - Key messages identified by the agency in terms of how to improve performance-based optimization and decision making with respect to asset management

Table 2: Agencies selected for interviews

Municipality (6)	Airdrie, AB Brantford, ON Calgary, AB	Courtenay, BC Halton Region, ON York Region, ON
Province/territory (6)	Alberta Manitoba Ontario	Prince Edward Island Saskatchewan Yukon
Regional transportation authority (3)	Metrolinx, ON TransLink, BC	Autorité régionale de transport métropolitain (ARTM), QC

Case studies

Following the interviews and in consultation with the Project Steering Committee, three agencies were selected for case studies. The purpose of the case studies was to show applications of performance-based decision processes and optimization methods involving the following: (1) cross-asset optimization; (2) development and implementation of a performance-based asset management program; (3) resource allocation within a transit agency; and (4) pavement management. The agencies selected for these case studies were the Regional Municipality of York, TransLink (South Coast British Columbia Transportation Authority), and Saskatchewan Ministry of Highways.

Visioning workshop

A visioning workshop was held in Winnipeg in November 2019 to identify the tools to be included in the practitioner toolkit. The selection of tools was based on the literature review, the online survey, and the telephone interviews. The intent of the toolkit is to assist practitioners with practical, easy to apply, transparent, and outcome-driven tools for performance-based decision making. The toolkit contains tools in three broad categories: data management; analysis and evaluation; and communication.

1.4 Report organization

Part A – Technical Knowledge Base of this report contains four chapters:

- *Chapter A.1* discusses the fundamentals of performance-based decision making. The chapter introduces the concept of performance-based decision making, describes elements of performance-based decision making, and discusses the benefits and challenges of performance-based decision making.
- *Chapter A.2* addresses asset management within a performance-based decision-making framework. The chapter identifies performance measures for asset management, discusses issues in performance-based asset management, and provides a cursory overview of

optimization methods in asset management. Details of these methods are provided in Part B – Practitioner Toolkit.

- *Chapter A.3* summarizes the state-of-practice for implementing performance-based decision making for asset management in Canada and the United States. The chapter presents the results of the agency survey conducted as part of this project, as well as three case studies conducted to learn more about current practices from select Canadian agencies.
- *Chapter A.4* presents a series of lessons learned from the study that support the implementation of performance-based decision making within asset management programs.

Part B – Practitioner Toolkit contains tools selected and developed based on information from the literature review, agency survey, telephone interviews and case studies. These tools are practical, transparent, outcome-driven, and based on sound technical knowledge. They are intended to guide practitioners at higher levels of decision making.

Part A:
Technical knowledge base

A.1 Fundamentals of performance-based decision making

This chapter introduces the concept of performance-based decision making, describes key elements, and discusses benefits and challenges.

A.1.1 What is performance-based decision making?

For the past two or three decades, transportation agencies in North America have increasingly applied performance management to support decisions that can help achieve desired performance outcomes. Performance management is “the practice of setting goals and objectives; an on-going process of selecting measures, setting targets, and using measures in decision making to achieve desired performance outcomes; and reporting results” (Grant et al., 2013).

In the United States, federal transportation legislation—especially the *Intermodal Surface Transportation Efficiency Act* (ISTEA) of 1991 and the *Moving Ahead for Progress in the 21st Century* (MAP-21) of 2012—has motivated state, municipal and transit agencies to implement performance management approaches. In Canada, although the same level of federal oversight does not exist, many transportation agencies use performance measures to evaluate their road networks (TAC, 2006).

While originating within the private sector, public transportation agencies have implemented performance management principles into their planning and programming processes (Grant et al., 2013; Barolsky, 2005; Cambridge Systematics, 2000) in order to:

- Improve program and project delivery with respect to desired performance outcomes
- Support decision making as it pertains to funding allocation and investments
- Provide transparency and accountability to the public
- Comply with good governance practices

Performance management principles can be applied within the short- and long-term planning and programming processes of numerous agency activities to achieve desired performance outcomes for the transportation system. These activities include transportation planning, design, construction, operations and safety, asset maintenance and management, and regulation. In addition, performance management supports internal organizational decisions concerning the overall program or project evaluation, investment alternatives and resource allocation (Cambridge Systematics, 2000; Cambridge Systematics 2010; Grant et al., 2013).

A.1.2 Elements of performance-based decision making

A.1.2.1 Performance management framework

Building on earlier work by Cambridge Systematics (2000) and Cambridge Systematics (2010), Grant et al. (2013) developed a framework for transportation agencies to implement performance management principles within their planning and programming processes. The framework contains elements common to performance management practices around the world (FHWA, 2010c). The framework, depicted schematically in Figure 1, comprises the following elements:

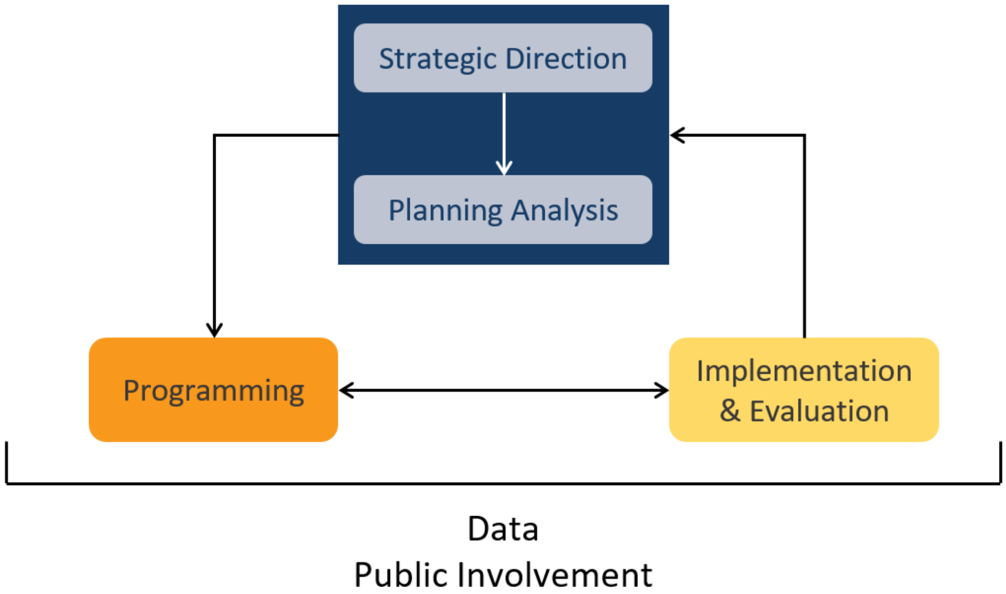
- *Strategic direction (i.e. Where is the agency going?)* – The strategic vision (or mission) of an agency is articulated based on stakeholder and public input, and is achieved by establishing:
  - Goals, which address desired outcomes
  - Objectives, which support the goals using more specific measurable or actionable statements
  - Performance measures, which support the objectives by providing a data-driven basis for analysis, monitoring and evaluation
- *Planning analysis (i.e. How will the agency get there?)* – Agencies conduct data-driven analysis to develop and prioritize investments and policies. This involves:
  - Identifying trends and targets (i.e. the desired direction or level of performance for a performance measure)
  - Identifying strategies and analyzing alternatives to assess approaches for achieving the trend or target
  - Developing investment priorities that support the attainment of trends and targets
- *Programming (i.e. What will it take?)* – This involves selecting specific investments that support the attainment of trends and targets while appropriately balancing relevant trade-offs. Programs are specified through:
  - Investment plans (of various temporal horizons
  - Resource allocation toward specific projects
- *Implementation and evaluation (i.e. How is the agency performing?)* – This occurs throughout project implementation and includes:
  - Monitoring of performance measures
  - Evaluating to what extent strategies or projects have been effective in meeting desired outcomes
  - Reporting results to policymakers, stakeholders and the public

As shown in Figure 1, the performance management approach starts with higher-level strategic direction and planning analysis. These elements contribute to programming decisions, which interact with implementation and evaluation activities. The outcomes of ongoing monitoring and evaluation feedback into refined strategies and plans, creating a management cycle that guides decision making over time (Grant et al., 2013).

Quantitative and qualitative data (including data collected from stakeholder and public consultations) fundamentally underpin all elements of the performance management approach (Grant et al., 2013). Consequently, there needs to be an emphasis on the collection of good data for monitoring, analysis, and decision making (Melaniphy, 2013; Cambridge Systematics, 2010). The creation of data management systems involves developing data governance and stewardship practices for data collection, cleaning, access, analysis and dissemination (Gharaibeh et al. 2017; Cambridge Systematics, 2010).

The toolkit in this report contains a set of tools for data management, including tools on data governance, quality assurance, data collection planning, data warehousing, data storage and data access.

Figure 1: Performance management framework



A.1.2.2 Performance measures

The process of selecting performance measures[1] begins with defining an agency's strategic vision, goals and objectives (Grant et al., 2013). Performance measures may be classified as inputs, outputs and outcomes:

- *Input measures* reflect the resources available within an agency to carry out a task.
- *Output measures* reflect the way resources are used, the scale or scope of activities performed, and the efficiency of converting allocated resources into a product.
- *Outcome measures* reflect the degree of success of the agency in achieving its goals and objectives.

Input and output performance measures are commonly used in practice, principally because they tend to be easier to monitor and communicate, less expensive to measure, provide more timely indications of performance (compared to long-term outcomes), and offer a basis for relating accomplishment to agency resources needed. While the literature emphasizes the need for increased utilization of outcome measures (Cambridge Systematics, 2000), agencies suggest that a blend of output and outcome measures should be considered (NCHRP, 2006).

While the number of performance measures should be few, they should cover the spectrum of an agency's objectives. Important requirements for high quality performance measures include, but are not limited to the following (Romell and Tan, 2011; TAC, 2006; Cambridge Systematics, 2000):

- *Measurability* – Does the agency have the capability and tools to consistently generate the measure? Are the data required available? Does the agency control the means by which the measure is produced?
- *Forecastability* – Can the measure be used reliably to compare alternative projects or strategies?

[1] The literature uses several terms interchangeably to refer to performance measures, including indicators, metrics and indices.

- *Clarity* – Do decision makers and stakeholders understand the measure?
- *Usefulness* – Does the measure relate directly to the issue of concern? Is the measure able to diagnose the problem?
- *Relevance* – Is the measure meaningful to track and useful to evaluate progress relative to established objectives?
- *Multimodality* – Does the measure apply to multiple modes of travel? Can it be applied objectively and fairly to make decisions across modal silos?
- *Temporal effects* – Does the measure have a consistent meaning over time? Can it be produced in a timely fashion to support decisions?
- *Geographic scale* – Is the measure applicable across appropriate geographic scales, including across jurisdictional boundaries?

Since an agency's selected performance measures determine the types of projects that get prioritized, it is important that they clearly relate to an agency's goals and objectives (Cambridge Systematics, 2000). With many transportation departments becoming more multimodal and the emphasis being removed from the roadway level of service (LOS) as the principal measure, many agencies use several measures to evaluate a system in one goal category. For example, an agency may define performance in the "mobility" category through measures of travel time, delay, transit load factors, and person-hours of travel, in addition to roadway LOS. Some agencies are implementing a tiered approach that allows more innovative measures to be added into the evaluation process as data collection capabilities improve.

As the practice of performance management has matured, agencies have begun to apply the framework to many activities, including asset management (see Chapter A.3). Hales et al. (2012) reviewed the various frameworks on proposed organizational performance measurement systems for transportation. The review summarizes recommendations that have been brought forward by different agencies over time:

- The FHWA has proposed six measures as important factors for a successful highway infrastructure system: safety, system preservation, system reliability, freight movement and economic vitality, environmental sustainability and livability.
- The Bi-Partisan Policy Centre (a Washington D.C. policy think tank) has recommended measuring transportation performance in five categories: economic growth, national connectivity, metro accessibility, energy security and environmental protection, and safety.
- AASHTO has proposed measuring transportation performance in six categories: safety, preservation, congestion, system operations, environment, and freight and economics.
- The U.S. Department of Transportation has proposed the following six transportation performance categories: safety, reduced congestion, global connectivity, environmental stewardship, security/preparedness/response, and organizational excellence.

A survey of Canadian jurisdictions found that performance measures used by jurisdictions should depend on an agency's specific conditions, goals, resources and audiences (TAC, 2006). The survey revealed that system preservation (i.e. asset management) was the most advanced and mature application of performance measures in Canadian jurisdictions. Safety performance was a priority interest, while sustainability and environmental quality were assessed to a limited extent.

While not specifically mentioned in the review by Hales et al. (2012), public transit agencies have also applied performance management approaches (Grant, 2011; Parks et al., 2010). Historically, the use of performance measures in public transit has been limited to issues such as ridership and service cost effectiveness. However, there is a need for more effective uses of transit performance measures to support investment decision making. Based on a U.S.-wide survey, two-thirds of all state departments of transportation indicated they have some public transit performance measures in place. Furthermore, some agencies are experimenting with the use of performance data to improve long-range planning decisions. Common measures used include:

- Ridership measures
- Availability measures (e.g. average days per week available)
- Cost and efficiency measures
- Quality-of-service measures
- Asset management measures for physical components (e.g. fleet age)
- Measures that focus on community impacts

A.1.2.3 Target setting and benchmarking

Targets provide a critical context for evaluating the effectiveness of investment decisions within a performance-based decision marking approach (Cambridge Systematics, 2010). The setting of targets is intertwined with the establishment (and refinement) of performance measures that meaningfully direct an agency’s activities towards its objectives and goals. Targets can provide a powerful internal motivation for an agency, especially when business units that consistently achieve targets are rewarded. Ongoing internal monitoring and evaluation, external benchmarking, or customer satisfaction feedback may trigger periodic revision of performance targets.

While target setting helps agencies to communicate what can and cannot be accomplished with certain funding levels and can aid in the understanding of public and elected officials, equity considerations and uncertainties related to data and technical tools generate some reluctance to apply targets within performance-based decision making. Agencies may emphasize the implementation of a performance-based strategy rather than the achievement of targets as the basis for accountability (Guerre et al., 2009).

Benchmarking is an important element of a performance-based decision-making approach (Crossett et al., 2019; Parks et al., 2010). Benchmarking involves using compatible measures and data to compare performance outcomes and business practices among organizations doing similar work, with the aim of continuously improving quality and performance. This practice allows agencies to gain broader perspectives, inform performance target setting, uncover noteworthy practices, identify areas needing improvement, spur innovation, and support transparency and accountability.

Two key types of benchmarking identified in Crossett et al. (2019) are independent benchmarking (where an individual agency benchmarks using public data and contacts peer agencies to gather information for comparison) and benchmarking networks (where a group of organizations agrees on a common set of measures, defines how they are calculated, and uses standard reporting to share results). The following steps in benchmarking are identified (Crossett et al., 2019):

- Set the stage by identifying a clear leader, developing a clear purpose statement, and establishing ground rules.
- Select peer agencies that share similar data availability, location, economy, transport system characteristics and others.
- Define the approach by choosing and defining measures with which to compare performance.
- Obtain data of sufficient quality for meaningful analysis. The data may be from national sources or peers.

- Analyze data to produce benchmark measures. Data should be clean and statistically significant.
- Identify noteworthy practices relating to organizational structure, data collection efforts, business and management processes, employee development, and tool implementation.
- Communicate results to executive management and stakeholders.
- Recommend improvements based on experience and continue the benchmarking process.

Within this general process, specific considerations may be necessary to perform benchmarking for an area of activity. Table 3 identifies activities and issues pertaining to the practice of benchmarking for asset management (Cooksey et al., 2011) and measuring transit agency performance (Parks et al., 2010).

Despite the apparent benefits of benchmarking, careful consideration needs to be given to ensure it provides meaningful direction to an agency's performance management approach. Acknowledging the challenges of benchmarking, TAC (2006) states that developing national rankings by performance measures is not informative due to agencies operating under different circumstances such as objectives or resource availability, or other external factors.

Table 3: Activities and issues for benchmarking – Asset management and transit agency performance

Asset management benchmarking model components (Cooksey et al., 2011)	Considerations for benchmarking transit agency performance (Parks et al., 2010)
Asset management culture: Measured in terms of the presence of asset management champions, perceptions of asset management, communication among an agency and its governing bodies, and an agency mandate to provide a catalyst for adoption	Consistent data collection is essential for a transit agency's reporting effort to have any value.
Quality information and analysis: Depends on a complete and accurate asset inventory, a common spatial referencing system, up-to-date asset condition data, and a formalized data management framework	Benchmarking can validate an agency's strengths and reveal opportunities for improvement. The approach from the start should be that an agency is committed to improvement.
Policy goals and objectives: Consists of the selection of priority investment areas, and establishment of meaningful performance measures and targets to link policy goals with planning decisions	Having a structure to routinely collect, analyze, report and store information can support a transit agency's day-to-day activities as well as support less-frequent benchmarking efforts.
Planning and programming: Consists of resource allocation and resource allocation decisions based on expected performance	It is important to distinguish between performance changes as a result of local changes, and changes as a result of data issues.
Program delivery: Involves the assessment of options while considering relative costs, benefits and risks, both immediate and long-term	It can be valuable to use per-capita performance measures that account for population and size of service area.
	Benchmarking networks can provide greater knowledge benefits and cost-sharing opportunities than individual peer-comparison activities.

Sources: Cooksey et al., (2011); Parks et al. (2010)

A.1.3 Benefits and challenges of performance-based decision making

Transportation agencies have increasingly implemented performance-based decision making because it offers considerable benefits to the agency and its stakeholders. The literature consistently cites these benefits as reasons to continuously refine the performance management approach. However, there are also considerable challenges. Some challenges have become more apparent as agencies refine their performance management approaches and become more sophisticated in their use of data and tools, more comprehensive in their application across modes and asset classes, and more capable of addressing competing objectives.

Table 4 synthesizes findings from the literature concerning the common benefits and associated challenges of implementing performance-based decision making.

According to a report by Cambridge Systematics (2000), some agencies may be more likely to benefit from the implementation of performance management approaches, particularly if they are charged with transportation system management in areas that:

- Are experiencing rapid growth
- Are highly urbanized or congested
- Have demonstrated support for multimodal transportation solutions and investments
- Have serious financial constraints or major infrastructure upkeep needs, or both
- Are in conflict over growth or investment policies or choices
- Are having difficulty meeting air quality attainment goals

Table 4: Benefits and associated challenges of performance-based decision making

Benefits	Associated challenges
Demonstrates link between agency goals, investment decisions, and performance outcomes	Restrictions on project funding using different funding sources can create challenges in selecting investments to support goals and objectives
Improves alignment between agency goals and those desired by users and the general public	Concerns about risks involved in setting targets since agencies have little control over external factors
Increases effectiveness of investment decision making by using data and performance measures to allocate resources in ways that achieve desired outcomes	High cost of data collection, analysis and management and the complexity of transforming data into information (i.e. meaningful performance measures)
Increases accountability and transparency in decision making	Time lag between the implementation of transportation system improvements and the resulting changes to performance measures can make the connection between decision making and results unclear
Improves internal strategic planning, management and evaluation of programs and services, especially across traditional agency silos	Agencies lack appropriate tools, analytical capabilities, and data governance practices to effectively apply performance-based decision making across internal departments

Benefits	Associated challenges
Improves understanding of alternative courses of action	Tools and data to accurately predict future performance outcomes from investments and strategies are unavailable or insufficiently developed for many performance categories
Minimizes life-cycle costs of keeping transportation systems in good condition	Addressing life-cycle issues at the program level requires the prediction of future performance and funding needs and the establishment of policies describing what work should be performed as a function of condition

Sources: Spy Pond Partners (2019), Gharaibeh et al. (2017), Grant et al. (2013), Hales et al. (2012); Cambridge Systematics (2006), TAC (2006), Neuman and Markow (2004), Cambridge Systematics (2000)

A.2 Asset management and performance-based decision making

This chapter identifies performance measures for asset management, discusses issues in performance-based asset management, and provides a cursory overview of optimization methods in asset management. Details of each of these methods are provided in Part B – Practitioner Toolkit.

A.2.1 Application of performance-based decision making for asset management

The application of performance-based decision making for asset management has become common practice for transportation agencies. In the United States, this has been motivated by federal legislation requiring states to develop risk-based asset management plans for preserving and improving the highway network, which includes summary conditions of pavements and bridges, asset management objectives and measures, performance gaps, life-cycle cost and risk management analysis, financial plans, and investment strategies (FHWA, 2016).

A policy-driven, performance-based approach to the allocation and consumption of resources for the management of transportation infrastructure is the foundation of transportation asset management (Neumann and Markow, 2004). According to Bryce et al. (2018), transportation asset management (TAM) is a broad concept, which has many definitions. However, one of the most recent definitions has been provided by MAP-21, which defined TAM as “a strategic and systematic process of operating, maintaining and improving physical assets, with a focus on engineering and economic analysis based on quality information, to identify a structured sequence of maintenance, preservation, repair, rehabilitation and replacement actions that will achieve and sustain a desired state of good repair over the life cycle of the assets at minimum practicable cost” (23 U.S.C. 101(a)(2), MAP-21 1103).

The underlying goal of asset management is to take a broad approach to resource allocation and programming decisions to provide greater value to the system and a good level of service for end users through improvements in program effectiveness and system performance (Cambridge Systematics, 2006). Furthermore, TAM practices enable agencies to optimize available funds toward improving the overall performance of transportation systems (Porras-Alvarado, 2016). The core principles of asset management are (Cambridge Systematics, 2006):

- Resource allocation decisions must be based on a well-defined set of policy goals and objectives.
- Asset management must be performance-based, where policy objectives are translated into system performance measures that can be applied on a day-to-day basis or for strategic management purposes.
- Funding allocation must be based on evidence resulting from analysis of how different funding allocations (e.g. preventive maintenance versus rehabilitation, or one asset class compared to another) will impact the achievement of policy objectives.
- All decisions must be based on credible, current and good quality data.
- Performance results must be monitored for impacts and effectiveness, and must be communicated regularly.

Neumann and Markow (2002) identify the following requirements for a strong performance-based asset management program:

- A comprehensive inventory of existing transportation infrastructure clearly detailing the characteristics of each asset type
- Measures of current condition and service level or performance for each asset class
- Analytical tools to forecast the change in condition, service, or performance over time
- Standards, or guidelines that provide information about the appropriate treatment for a given condition
- Models to estimate the cost of each treatment and the level to which the facility is repaired or its life extended
- Models to forecast the implications of investments associated with various treatments and their effect on system performance and transportation users

Notably, performance measurement alone does not result in effective asset management (Amekudzy and Meyer, 2011). Performance measures must also be applied in resource allocation decision making to ensure strategic goals are achieved. A successful asset management program has fewer, clearer strategic goals that are associated with performance measures used in resource allocation decisions. Moreover, efforts are necessary to address uncertainties and procedural gaps to improve the quality of performance outcome data and the overall performance management process.

A.2.2 Performance measures for asset management

As in any area of agency activity, the development and application of meaningful performance measures are critical for an effective asset management system. Performance measures are indicators of system effectiveness and support the efficient allocation of limited resources amongst competing objectives and alternatives (Haas et al., 2014). However, performance measurement is still evolving in the asset management context, and agencies are at varying levels of maturity (Amekudzy and Meyer, 2011). Hence, given their importance in resource allocation, any framework for performance measures should include functional, technical, environmental, safety, economic and institutional considerations (Haas et al., 2014).

Haas et al. (2014) indicate that performance measures for asset management should be able to:

- Assess the physical condition and the resulting level of service provided to road users
- Determine asset value
- Serve as a monitoring mechanism for assessing the effectiveness of policies and their compliance with predefined policy objectives
- Provide information to users
- Serve as a resource allocation tool that helps to quantify the relative efficiency of investments across competing alternatives
- Serve as a diagnostic tool for early identification of accelerated deterioration of assets

Cambridge Systematics (2006) identifies performance measures for good asset management practices, specifically those that pertain to the preservation of assets, mobility and accessibility, operations and maintenance and safety. Among these areas, the development and application of performance measures for physical assets (pavements and bridges) are the most mature. Performance measures for other goal areas (e.g. mobility, accessibility, safety) tend to be less advanced.

To illustrate the recent state-of-practice, Box 1 summarizes findings from a U.S.-based peer exchange on performance measures for asset management. In general, the exchange revealed that states were ready to implement performance measures for pavements, bridges and safety, but were less ready in other areas (Guerre et al., 2009). Box 2 provides a municipal perspective and lessons learned from the implementation of performance-based decision making for pavement preservation.

Box 1: Findings from a peer exchange on performance measures for asset management

Pavement performance measures
IRI was the only pavement condition measure collected by all departments of transportation. However, two reported issues with IRI are: (1) inconsistency with data collection; and (2) inability to represent the overall structural condition. Different equipment and protocols were cited as issues causing discrepancies in IRI collection among different states. Some states measure present serviceability (PSR), while others measure remaining service life or combine structural adequacy and ride quality into a single measure.
Bridge performance measures
Structural deficiency is the most common measure used for reporting bridge condition. Three peer exchange recommendations follow: - Use a measure that helps to identify deteriorating bridges before they become deficient. Having good/poor/fair thresholds would help strategies for preventative maintenance, rehabilitation, or reconstruction. - Consider structural deficiency caused by deck ratings, versus overall deficiency. Bridges that are deficient due to deck area may be a lower priority than bridges with superstructure or substructure deficiencies. - Consider counting fracture-critical bridges as a measure.
Other goal areas
Safety performance measurement is advancing. Two recommendations from the discussions were: (1) a smaller set of measures would help with focus and improve overall success; and (2) acknowledge differences among states in terms of baselines and set unique goals based on them. In addition, participants recommended the use of benefit-cost analysis in the measurement process and discouraged the use of “worst-first.”

Source: Guerre et al. (2009)

Box 2: Lessons from a municipal performance-based pavement preservation program

Criteria for selecting a performance measure
The San Francisco Metropolitan Transportation Commission's (MTC) pavement preservation program applies outcome-driven performance measures to support maintenance practices and funding allocation. The challenge was selecting a "one size fits all" performance measure that could be fairly applied across all local jurisdictions with varying sizes. The Local Streets and Roads Working Group determined that the performance measures should: • Be measurable • Be as objective as possible • Enable fair application and assessment • Utilize data that is widely available • Be meaningful (i.e. promote asset management objectives) The developed performance measure that complied with the listed criteria was based on the ratio of actual preventative maintenance expenditure to the expenditure amount recommended for each jurisdiction using the optimization software StreetSaver. The allocation model allocates regional funding based on a combination of factors including population, lane mileage, arterial and collector shortfall share and performance.
Lessons learned
The lessons learned from the process of implementing performance measures follow: • Asset management practices must be implemented prior to the adoption of performance measures where there is access to quality inventory and condition data. • A bottom-up, collaborative approach is key to developing measures that are accepted by local jurisdictions. • The setting of clear guiding principles is important for developing outcome-driven performance measures. • Transparency of how performance measures are calculated and how they are used for resource allocation is important to ensure that they are fair and unbiased.

Source: Romell and Tan (2011)

A.2.3 Issues in performance-based asset management

Several issues need to be considered for the successful development, implementation and operation of a performance-based asset management. These considerations may be viewed as both barriers and opportunities. Some considerations may reflect potential or existing problems or pitfalls that have been commonly encountered and require specific actions to overcome (e.g. lack of integration, working in silos, limited data analysis capabilities). Other considerations, such as sustainable development, represent the continuing evolution of asset management towards sustainable systems comprising economic growth, social development and environmental protection. The following issues are addressed here:

- Leadership, administrative and institutional issues
- Life cycle issues
- Sustainable development issues
- Operating and capital issues

- Issues involving priority setting between program elements
- Data-related issues

A.2.3.1 Leadership, administrative and institutional issues

According to Cambridge Systematics (2006), one of the most important aspects of a transportation asset management program is meeting the needs of people within an organization. A significant challenge is that the organizational structures of most agencies are functionally segregated. This results in the need to help people understand the benefits of the asset management process from the perspective of the entire agency and not only their individual perspectives. Ensuring that senior management buys into the process is critical to success. This is reinforced by Lownes, Zofka and Pantelias (2010), who argue for the need to have visible and active champions to guide and support the successful implementation and operation of a transportation asset management program. The authors state that strong and consistent support from senior leadership is essential to increase program awareness.

Amekudzi and Meyer (2011) identified the following pressures that can influence an agency's approach to performance measurement and asset management procedures:

- Leadership changes at senior levels
- New funding sources
- Political influences
- External mandates for benchmarks
- Performance reporting

Leadership changes are not the only human resource issue that can influence an agency's approach to performance measurement and asset management. Spy Pond Partners (2015) discusses the importance of knowledge management for transportation agencies. The report defines knowledge management as an umbrella term for a variety of techniques for building, leveraging and sustaining the know-how and experience of an organization's employees. Knowledge management is critical, as knowledge about what to do, when and how to do it and what not to do is critical to the success of asset management programs. In addition, knowledge management can help build in-house expertise and minimize the impact of workforce transitions. The report presents the following four steps for knowledge management:

1. *Assess risks and opportunities* – This step identifies focus areas based on current characteristics such as expected retirements, mentoring, process documentation and information storage practices.
2. *Develop a knowledge management strategy* – This step involves producing a written document that defines what the agency hopes to accomplish and how. This step should focus on assessing the risks of knowledge loss and improving agency adaptability.
3. *Create a knowledge management implementation plan* – This step defines the goals, outlines initiatives the agency wants to pursue and designates a lead person to move it forward.
4. *Monitor results* – This step ensures accountability by measuring the costs, outputs, exposure and outcomes of the knowledge management program.

In addition to those pressures, there is also the issue of competing objectives between individuals or divisions within an organization, resulting from different internal priorities from stakeholders (e.g. the pavement division may be focused on asset preservation, while the bridge division may be focused on asset maintenance), or from focus on short-term budgets (FHWA, 2007). These competing issues need to be resolved through alignment with policy goals, understanding of trade-offs and consensus building.

Haas (2011) presents the following important ingredients for success as it relates to performance-based pavement asset management:

- Leadership and commitment, institutionally and individually
- A comprehensive pavement and asset management framework
- A vision of technical, economic and institutional needs in asset management
- An understanding of available technologies and best practices, support for continuing advancements and recognition of the driving forces in the evolution of and future challenges for pavement management
- Acquisition of and/or access to data and information
- A broadly based, experienced team
- Incorporation of a life-cycle approach
- Acceptance of a reasonable degree of risk
- Creation of product(s)/guides which serve the user community
- An inherent philosophy that succession planning is a process that continues over time not only for people but also for advancements in technology, information, education and training, commitment of resources and sustainability

A.2.3.2 Life cycle issues

Life-cycle costs are the series of costs incurred to procure or construct an asset and then maintain the asset over its life cycle (Spy Pond Partners, 2019). An asset owner needs to make timely investments to keep an asset in good repair and reduce the likelihood of making costlier repairs later. Consider an example from Texas, where costs incurred over a 10-mile (16-km) highway stretch was demonstrated using two investment strategies: repeated repairs over time; and infrequent, reactive maintenance. With the repeated repairs, the overall service conditions throughout the asset life were improved and the overall asset costs were over 15% lower (Spy Pond Partners, 2019).

According to Spy Pond Partners (2019), practices are well established for using life-cycle cost analysis to compare different design alternatives for pavements and bridges. However, these practices are typically intended for applications at the project level, after a substantial amount of detail has been established. Practicing effective asset management requires considering life-cycle costs programmatically, using life-cycle cost concepts to establish budget levels and predict future performance and funding needs. Applying concepts at a program level requires establishing policies describing what work should be performed over time as a function of condition. Essentially, life-cycle costs should be a key consideration in all project selection processes, including those within cross-asset resource allocation.

The life cycle of an asset includes planning, construction, maintenance, renewal and ultimately, disposal (AASHTO, 2013). Life cycle planning should consider issues such as how decisions will affect the safety performance of an asset and what allowance should be made for climate change when designing a new asset with a long life. Opportunities for life-cycle cost reduction are typically greatest in the planning stage, where approximately three-quarters of the factors affecting costs are decided (AASHTO, 2013). This stage involves aspects such as scoping, option evaluation and selection. Once the asset is built, the focus becomes managing and maintaining it in the most cost-effective manner and doing the right work at the right time to get the best value for investment in terms of asset services delivered.

Existing asset management systems (e.g. pavement and bridge management systems) may not fully integrate all aspects of life-cycle costs. For example, Haas et al. (2011) identify the following pavement management system (PMS) improvements related to life-cycle costs:

- Quantifying the benefits of PMS and component activities like data collection
- Very long-term life-cycle analysis protocols
- Quantifying the benefits, or extra costs, of varying risk exposure
- Incentive programs for improving PMS processes and application in both the private sector and public-private partnership (P3) contracts

A.2.3.3 Sustainable development issues

Sustainable systems comprise economic growth, social development and environmental protection (Faghih-Imani and Amador-Jimenez, 2013).

The International Transport Forum (2018) identifies the following recommendations with respect to sustainable development as it relates to asset management:

- There is a need to involve asset managers early in the process of implementing new technologies and logistical systems, since adapting design and maintenance practice takes time.
- A proactive approach to asset management is required to handle problems of ageing infrastructure, which prevents major structural damage before it occurs, leading to optimal usage of assets.
- Monitoring traffic and especially truck traffic activity is essential for sustainable asset management. However, it is critical to not just count trucks, but rather to understand the underlying nature of road freight transport demand. This includes geographic, temporal and modal distributions; interrelationships among commodities, trip distances and truck configurations; and new logistics trends.
- The “do nothing” approach to implementing regulations is unsustainable and the result will be an ongoing increase in the volume of heavy traffic and increased wear of road infrastructure.

In addition, the International Transport Forum (2018) presents the following policy categories that can be used to extend the life of road assets:

- *Demand-responsive policies* – These policies aim for a proactive approach to maintaining assets and anticipating growing demands on the road networks. Such practices should eventually apply across all asset groups.
- *Policies that regulate demand* – These policies aim to improve the productivity of road transport, utility of road use and improve cost recovery to encourage behavioural change in transport operations.
- *Policies that influence demand* – These policies aim to influence real-time and longer-term road freight transport decisions and behaviours and improve the environmental performance of road freight transport. An example of such a policy includes infrastructure pricing that encourages shippers and carriers to reduce the number of kilometres driven to achieve the freight task.

Highlighting a more local example, the Ontario Ministry of Transportation (MTO) has implemented pavement preservation strategies as a sustainable way to maximize cost savings associated with the repair and maintenance of pavements (Chan, Lane and Kazmierowski, 2011). For each of these strategies (crack sealing, slurry seal, micro-surfacing, chip seal, ultra-thin bonded friction course, fiber modified chip seal, hot mix patching and hot in-place recycling), MTO compared the energy consumption and greenhouse gas (GHG) emissions generated versus typical rehabilitation and reconstruction treatments. This approach has been found to improve pavement quality and durability and extend pavement service life, while reducing energy consumption and GHG emissions (Chan, Lane and Kazmierowski, 2011). The authors recommend the following initiatives for implementing more sustainable pavements:

- Build on current industry/ministry partnerships in the development of improved specifications and design/construction procedures
- Encourage continued innovation by the province's pavement preservation contractors
- Support dedicated research programs to advance the technology
- Increase technology transfer at the provincial and national levels to accelerate the adoption of pavement preservation concepts

A.2.3.4 Operating and capital issues

Appropriate budgeting and allocation of funds for operations and capital investments is a challenge within asset management, but one that performance-based approaches can help address. Cambridge Systematics (2008) asserts that good asset management, coupled with meaningful financial reporting is essential for efficiently and effectively maintaining infrastructure systems. More specifically, that report concludes the following regarding the financial implications of performance-based asset management decisions:

- There is often a reciprocal relationship between performance targets and budgets, where performance targets drive budgets, which, in turn, may further drive performance targets.
- Several transportation agencies view the comparison between planned and actual expenditures as far less important than the comparison between targeted and actual conditions.
- The preparation of performance management information generates significant interaction between asset managers and financial units, which is valuable for agencies.
- Where a passion for asset management does not exist, little progress can be made from a financial perspective.

Grant (2011) reports on a survey of 43 transit agencies in the U.S. regarding performance-based decision making. The survey found that 40% of participants reported using public transportation performance measures to support operational funding allocation and 25% indicated they are using public transportation performance measures to support capital funding allocation.

Despite the important link between performance-based asset management and financial decision making, not all agencies successfully link these administrative processes. For example, as part of an international scanning tour of performance management practices in Australia, Great Britain, New Zealand and Sweden, FHWA (2010c) identified that despite carefully defined, planned, documented and operated performance management programs, performance management did not play a material role in budgeting at the legislative levels. While performance management demonstrated how funds were spent and to what end, the systems did not appear to include a feedback loop that triggered legislative appropriation decisions.

A.2.3.5 Issues involving priority setting between program elements

As asset management programs mature, issues involving priority setting between program elements have emerged. Such issues can span across modes and/or asset classes.

Wiegmann & Yelchuru (2012) developed an analysis framework for use as a guide to allocate highway system preservation resources across various asset groupings, preservation activities and regions. The report is based on an extensive literature review and a series of interviews on the practices of resource allocation. The framework involves the computation of preservation needs based on strategic decisions, goals and information about inventories, costs, performance ratings and deterioration rates. Allocation adjustments are optimized based on needs, available funding and constraints. If available funding does not match preservation needs, adjustments can be made to the performance goals or overall funding commitment. Key conclusions from the report follow:

- Information on inventory, condition, deterioration and preservation cost data is scarce among transportation agencies, making it challenging to apply a complete analytical approach for resource allocation.
- Deterioration is a strong driver of preservation needs. When preservation need exceeds funding resources, performance is expected to regress. In these cases, optimized allocation of available funds seeks to minimize performance regression across asset groups.
- Further research is needed to support improved methods for determining average deterioration rates.
- Preferred optimization strategies differ across multiple agencies; therefore, agencies should exercise the development of optimization functions that are well suited to their needs and based on experience from other agencies.

More recently, Maggiore & Ford (2015) presents an overarching framework for the optimal allocation of limited resources across asset classes. General conclusions from the study follow:

- A challenge facing many agencies is the overall lack of a suitable list of candidate projects with adequate information on project details and performance impacts. The suggested approach is “bottom-up” in nature, where all possible projects are pooled and prioritized.
- Management systems and tools should be applicable to project-level “bottom-up” and network-level (“top-down”) optimization approaches.
- Establishing performance targets and relative weighting (importance) of performance measures requires significant and iterative policy development efforts.

Similarly, FHWA (2012) identifies three key elements of resource allocation in terms of investments:

- Development of investment plans to help describe trade-offs and provide a system-level understanding
- Short-range programming to help document specific commitments
- Targets and trends established based on what is possible with current resources and what is expected given the strategies and investments

The report states that linking system performance with project programming requires consistent definition and application of outcome measures. In addition, some agencies use a corridor approach that develops strategies for major corridors and then prioritizes based on funding and constraints. Many agencies use optimization techniques that do not necessarily identify the best projects, but rather emphasize projects that maximize performance of a full program, subject to constraints. Successful implementation requires tracking performance and comparison with expected targets.

A.2.3.6 Data-related issues

As described in Chapter A.2, effective implementation of performance-based decision making relies on the availability of reliable data. Among the key challenges associated with performance-based asset management identified in the literature, many relate to the cost-effective production and maintenance of consistent, timely and quality data (see Table 4).

Gharaibeh et al. (2017) summarizes the following general data-related issues associated with a performance-based asset management program:

- A more top-down data governance approach is desired, by which governing bodies can successfully leverage the value of data stored in various agency silos for increased integration and sharing.
- Although transportation agencies collect a wealth of data including pavement and bridge inventories, traffic monitoring data and collision data, many agencies do not have a reliable estimate of the amount of data they maintain. Furthermore, there is a need for designated data stewards and the use of proper data warehousing systems.
- Issues such as multiple location referencing methods and incompatible data management systems are impediments to proper data integration. The increased use of web-based data storage and compatible database management systems are key aspects to agency success.
- There is a strong focus toward data timeliness, accuracy and access security.
- Data consistency is the quality dimension least evaluated by transportation agencies.

A.2.4 Optimization methods in asset management for resource allocation

A.2.4.1 Need for decision-making tools

The allocation of limited resources within an agency requires technical tools and sound judgement by a range of decision makers. There are many potential methods and techniques that are used for the optimization of resource allocation. The applicability or effectiveness of each method depends on many issues, including available agency resources, overarching agency goals and preferences and the asset class to which the specific method is applied.

According to Uddin, Hudson and Haas (2013), several considerations should be accounted for when selecting an appropriate economic evaluation method for resource allocation among programs or options:

- The level of importance of the initial capital expenditure in comparison to future expected expenditures
- The level of understandability of the method by the decision makers
- The suitability of the method to the requirements of the agency
- Whether measures of benefits or effectiveness are to be included in the analysis

Cambridge Systematics (2005) states that existing tools are not well suited to guiding decision-making processes that cross the boundaries of asset type (e.g. pavement versus bridge), mode (e.g. highway versus transit), work class (e.g. maintenance, operations, construction), or objective (e.g. safety, preservation, mobility). The report identified several cross-boundary challenges:

- *Preservation versus mobility* – Making explicit trade-offs across programs that may have very different objectives and performance measures
- *Maintenance versus capital* – Determining the best combination of maintenance and capital investments in infrastructure to minimize life-cycle costs and assessing the cost-efficiency of different preventative versus deferred maintenance policies
- *Cost-effective solutions* – Determining the most cost-effective solution to a problem, without being constrained to a particular type of solution (e.g. operational, maintenance, or capital)
- *Optimal combinations of projects* – Identifying groups of projects that can result in the highest long-term benefits and cost savings (e.g. through coordinating scheduling of work for a particular location) and identifying groupings of projects of different types that have corresponding effects
- *Impacts of project needs criteria and design standards* – Exploring how variations in design standards or project needs criteria might affect long-term costs and system performance measures
- *Multi-objective evaluation* – Understanding the impacts of a given group of projects, recognizing that each project may have both positive and negative impacts with respect to different performance objectives and cross-project effects may be at work (i.e. one project may have the effect of reducing or increasing the effectiveness of a second project)

Hence, there exists a wide range of considerations and challenges associated with the optimization of funds in asset management. Agencies must be cognizant of these issues when applying optimization methods that suit their unique goals and objectives.

Based on these challenges, Cambridge Systematics (2005) identifies the need to enhance existing and develop new asset management tools within five categories:

- *Management systems* – Tools in this category enhance existing pavement and bridge management systems that provide inventory and condition information, simulate the deterioration and application of different projects and rank candidate projects based on conditions and benefit/cost analysis. They also support maintenance management systems implemented to plan, schedule and track maintenance activities.
- *Investment level trade-off analysis* – Tools in this category analyze performance trade-offs within and across investment categories for a range of budget levels.
- *Tools that identify needs and solutions* – Needs identification is a core function of pavement, bridge, safety and congestion managements systems. Integrated approaches are used to identify needs and solutions using the outputs of management systems together with GIS and query tools.
- *Tools that evaluate and compare options* – These tools are used to evaluate project/strategy options and/or prioritize projects through benefit/cost analysis. Life-cycle costs are typically analyzed as part of a detailed project-level analysis of alternative design choices for bridge and pavement projects.
- *Tools that monitor performance and results* – These tools help an agency track progress towards performance goals and objectives and support internal and external communication.

A.2.4.2 Conventional decision methods in asset management

While engineering judgment influences any decision making process, sole reliance on such judgement other than in the most straightforward cases may lead to bias, inconsistency and sub-optimal results (Uddin, Hudson and Haas, 2013). In the context of asset management, the collection and maintenance of basic asset inventory and condition data enable a more data-driven decision-making approach. The availability of data, however, does not necessarily lead to superior decision making. Faced with resource allocation challenges associated with ageing assets, large and diverse asset inventories, insufficient funding, long life cycles and competing priorities, some agencies use asset condition data but resort to a "worst-first" management approach. The worst-first approach addresses immediate defects or problems, but leaves no resources for preventative maintenance, upgrades or transportation asset management planning (Feunekes et al., 2011; Lownes et al., 2010; Chan, Lane and Kazmierowski, 2011).

Engineering economics tools help resource allocation decisions by monetizing various agency, user and societal costs and benefits over the life cycle of an asset (Uddin, Hudson and Haas, 2013). These tools enable comparison and evaluation of alternative courses of action by converting various types of costs and benefits into monetary units and accounting for the time value of money through the use of an interest rate (or discount rate), even if alternatives are expected to have different service lives.

The present worth (or net present worth) method is perhaps most familiar. When applied to asset management, this method allows projects or programs with varying cash flow timelines to be compared with each other in present terms. The key concept is that funds in-hand today can be invested and gain value over time and are thus worth more than funds of the same amount that are only available at some time in the future. Alternatively, the internal rate of return method determines the discount rate (or interest rate) at which the costs and benefits of a project are equal. In this context, a decision maker is presented with evidence about the investment potential of various alternatives. This may lead to decisions not to spend money unless a desired rate of return can be achieved (Uddin, Hudson and Haas, 2013).

The concepts of engineering economics underpin what Uddin, Hudson and Haas (2013) identify as near-optimization methods for resource allocation and asset management decision making. The benefit-cost method is widely used for infrastructure projects, particularly for large projects. In this method, the ratio of the benefits and costs of a project are calculated, either in terms of present worth or equivalent uniform annual worth (i.e. annual cash flow). Project alternatives with benefit-cost ratios greater than 1.0 are compared on an incremental basis. This involves calculating the benefit-cost ratios on the increments of expenditures and investments for successively higher-cost alternatives. The initial increment considered is that of going from a "do-nothing" alternative to the first feasible alternative. If the incremental benefit-cost ratio is greater than 1.0, the assessed alternative becomes the base of the next increment. This pair-wise comparison is repeated until all alternatives have been examined.

Alternatively, the cost-effectiveness method, while still considered sub-optimal, provides an opportunity to consider how well a project meets specific performance objectives (Khurshid et al., 2011; Uddin, Hudson and Haas, 2013). This method, which is extensively used for pavement management, compares alternatives with varying performance curves. In this context, the effectiveness of an alternative is calculated as the area under the performance curve multiplied by traffic volume and the length of the road section. Since cost-effectiveness values (i.e. the ratio of effectiveness divided by the present worth of costs over the life of a facility) are expressed as indices, they should only be used for comparison purposes.

The application of engineering economics principles to asset management has become common practice, despite noted limitations:

- Results of economic analyses are sensitive to the selection of a discount rate, which is subject to uncertainty because it may change over the analysis period.
- The monetization of certain types of costs and benefits may not be straightforward or even recommended. While monetization offers a common unit of comparison, it may disregard qualitative information on intangible impacts of alternatives (e.g. environmental or social costs) (Amin and Amador, n.d.). Some asset management approaches utilize a level-of-service (LOS) concept to enable stakeholders to evaluate whether objectives have been achieved (AASHTO 2013; Hwang and Lee, 2018).
- In an economic analysis, it is not always clear what constitutes a cost or benefit (Newnan et al., 2006). This arises because many projects or programs impact multiple stakeholders with different viewpoints. Moreover, the categorization of costs and benefits does not necessarily align with the entity responsible for bearing those costs or realizing the benefits.
- An economic analysis may provide information on the most economically attractive alternative, but does not necessarily offer insights about how well an alternative supports one or more predefined and potentially conflicting performance objectives (Faghih-Imani and Amador-Jimenez, 2013).
- While adaptable, economic analyses do not inherently integrate concepts of risk and uncertainty into the analytical process (Li and Madanu, 2009).
- While there is evidence of successful application of life-cycle cost analyses within a single asset class (Bhargava et al., 2013; Al-Kathairi, 2014; Haas et al., 2014), significant challenges remain when considering optimal resource allocation across different asset classes.

A.2.4.3 Risk assessment and risk management

Risk assessment and risk management techniques have been increasingly integrated into asset management practices (Boadi and Amekudzi, 2013; Boadi et al., 2015; Mohseni et al., 2017), in order to:

- Proactively address shortcomings associated with uncertainties of various decision input parameters (e.g. through the application of various probabilistic methods)
- Make better use of limited resources
- Help minimize threats, maximize opportunities and optimize achievement of objectives
- Provide adequate levels of service to stakeholders

Risk assessment refers to the scientific process of measuring risks quantitatively and empirically. It typically occurs before risk management, which is a qualitative process that involves judging the acceptability of risks and implementing measures to reduce them to acceptable levels (Amekudzi and Meyer, 2011; Proctor and Varma, 2012; AASHTO, 2013).

Amekudzi and Meyer (2011) identify key questions that should be asked during the risk assessment and management processes:

- *Risk assessment questions* – What can go wrong? What is the probability that it will go wrong? What are the consequences associated with the failure?
- *Risk management questions* – What can be done to mitigate the risk? What are the associated trade-offs with respect to costs, benefits and risks? What are the impacts of current management decisions on future options?

Cambridge Systematics (2009) proposes a risk management process that considers these questions within the following steps:

- Identify critical infrastructure elements and the magnitudes, probabilities and spatial distribution of hazards and threats
- Develop a profile of potential threat/hazard scenarios
- Estimate scenario consequences, measured in terms of safety and mobility metrics such as human safety, property damage and system/agency mission disruption
- Identify risk management strategies and countermeasures for each threat/hazard
- Establish risk mitigation priorities, based on countermeasure effectiveness and estimated costs

More broadly, these steps may be executed within an overarching framework for optimal allocation of limited resources across asset classes, as proposed by Maggiore & Ford (2015):

- Include risk mitigation objectives when developing overall agency goals and objectives
- Develop risk assessment scores as a function of probability and consequence and include these as performance measures within asset management frameworks
- Identify projects which will help mitigate deteriorating structural performance and consider the uncertainty of costs and benefits
- Determine the “must-do” projects (i.e. those projects that, if not selected, pose unacceptably high risks)
- Assess the financial risk of alternative funding scenarios

Finally, despite its benefits, risk management is subject to limitations concerning (Boadi et al., 2015):

- The level of effort required to implement the risk assessment and management processes
- The difficulty of using appropriate measures to communicate risks
- The tendency to disregard qualitative inputs in an increasingly quantitative analytical exercise
- The potential to attribute successful outcomes to a particular risk mitigation strategy, when external factors may have been more influential
- The challenges of effectively monitoring and assessing the effectiveness of risk mitigation and management efforts
- The failure to effectively communicate risk information and the benefits of risk management approaches

A.2.4.4 Multi-objective or trade-off analysis

One of the core principles of asset management is the analysis of options and trade-offs (FHWA, 2007). This involves considering how different resource allocation decisions affect the achievement of policy objectives and the limitations posed by realistic funding constraints given the range of appropriate options and trade-offs.

Bai et al. (2012) explain that trade-off analysis examines the consequences of different optimal solutions under different funding and performance scenarios. This approach strives to achieve a balance among different performance objectives under a limited budget. Trade-off analysis can be between two alternative projects, between costs and the gained benefits (i.e. performance), or between two performance measures where benefits in one performance measure can be substituted for another performance measure (e.g. safety versus congestion).

Different transportation assets have different performance measures that must be considered to capture the overall effect of each project (Bai and Labi, 2009; Bai et al., 2012; Boadi and Amekudzi, 2013; Bryce et al., 2018). The goal is to maximize or minimize objective functions created for each performance measure, thus creating multi-asset and multi-objective mathematical problems. Network-level performance measures such as average condition or average crash rate are used in cross-asset multi-objective decision making. Budgetary constraints can be incorporated within the problem, or cost can be considered a performance measure with its own objective function.

The concepts of Pareto solutions and criteria weighting underpin multi-objective or trade-off analyses (Osyczka, 1985; Nakayama et al., 2009; Sinha et al., 2009; Wu et al., 2009; Bai et al., 2012; Maggiore & Ford, 2015). A Pareto solution identifies the set of alternatives that cannot be improved with respect to one criterion without degrading performance for other criteria. Pareto solutions are helpful when there are no agreed-upon relative weights for the criteria. If criteria are weighted, alternatives can be scored and ranked accordingly. Each alternative's score is the sum of the products of the criteria scores and weighting factors. Weights are usually calibrated to reflect stakeholder preference. So, in essence, the decision maker has to select a satisfactory solution from a set of Pareto optimal solutions based on some specific judgment and value system.

The literature identifies numerous multi-objective optimization methods applicable to transportation asset management. Table 5 summarizes key features of these techniques.

Table 5: Multi-objective optimization methods applicable to transportation asset management

Method	Description
Weighting sum method	Combines various objective functions into a single objective function by assigning weights to the objective function components and varying the weights to influence the Pareto set of solutions
Goal programming method	Minimizes the weighted sum of deviations of all objective functions from their respective goals
Multiplicative utility function method	Computes the utility of each of a set of alternatives; the underlying principle is that all selected criteria are mutually utility independent, where the level of performance of one criterion is independent of how the other criteria perform
Compromising programming method	Identifies solutions that are closest to the ideal solution by some measure of distance, which is often the minimization of normalized deviation as measured by selected metrics
Ɛ-constraint method	Optimizes one arbitrarily selected objective while converting all remaining objectives into constraints with specified boundaries
Multi-attribute utility theory	Mathematical framework for analyzing and quantifying choices involving multiple competing outcomes, which can be used to investigate trade-offs among competing infrastructure asset classes where it is practical to consider potential shifts in funding from one class to another; the analysis measures the decision maker's risk attitude toward the selection of one type of resource allocation formula versus another for the performance of infrastructure
Analytic hierarchy process	Designed for subjective evaluation, providing weights to express the relative importance of a set of alternatives based on multiple criteria

Method	Description
Genetic algorithms (variations)	A suite of search techniques based on the mechanics of natural selection for solving complex combinatorial optimization problems; the search and the generation of solutions are conducted concurrently, with new solutions being generated through reproduction, crossover and mutation until a prescriptive condition is satisfied

Sources: Fwa et al. (2000); Amekudzi et al. (2001); Hall et al. (2004); Li and Sinha (2004); Gharaibeh, Chiu and Curian (2006); Mrawira and Amador (2009); Scheinberg and Anastasopoulos (2010); Lin and Lin (2011); Bai et al. (2012); Wu et al. (2012); Boadi and Amekudzi (2013); Farashah and Tighe (2014); Uddin, Hudson and Haas (2013); Bai et al. (2015)

A.2.4.5 Cross-asset optimization

Cross-asset resource allocation is the process of determining how to allocate funding across multiple types of assets or investments (Spy Pond Partners, 2019). It allows for the effective allocation of funds across multiple classes of assets, including pavements, bridges and appurtenances. Despite technical advances, most current transportation asset management practices address resource allocation only within a single asset class, leading to a siloed approach, which constricts the impact on the overall transportation system's performance. Cross-asset resource allocation has been addressed using informal methods in which a small group of decision makers arrives at a negotiated solution after subjectively reviewing the available data, often relying heavily on past precedent or formula allocations. In recent years, transportation agencies have sought to use more structured approaches.

The literature review revealed several key themes associated with cross-asset resource allocation, as follows (Fwa and Farhan, 2012; Porras-Alvarado et al., 2016; Bryce et al., 2018; Spy Pond Partners, 2019):

- It is important to recognize that projects spanning multiple assets satisfy multiple objectives. Weighting the benefits of the various objectives allows performance scores to be developed to compare the benefits of project options on a level playing field.
- Equity is an important concept and should be considered within cross-asset resource allocation decision models. This implies that: programs should receive the same amount of resources as they contribute; funding allocation strategies should favour disadvantaged programs; and resources should be allocated according to the actual needs of different programs.
- The concept of envy is critical in accounting for and minimizing inequities among multiple programs and assets.
- It can be beneficial to utilize familiar metrics to an agency when assessing the performance of asset systems.
- It is important to consider the impacts of different funding levels on program response (top-down management approach), as well as the specific performance implications of a potential project (bottom-up approach).
- The ultimate decision to select a project or series of projects depends on the goals, objectives, visions and budget constraints of an agency.
- In any case, it is important to involve subject-matter experts and decision makers from all backgrounds and specialties involving asset management.

Despite the challenges associated with cross-asset resource allocation, approaches have been developed to help agencies with this task (Bryce et al., 2018; Spy Pond Partners, 2019):

- *Delphi method* – In this method, resource allocation decisions are made by a committee of agency decision makers and experts (either internal to the agency or from a third party) from different subject areas. The method uses an iterative process to forecast outcomes of different resource allocation decisions and then refine decision making until a consensus is reached.
- *Multi-objective decision analysis (MODA)* – A MODA has many similarities with the multiple-objective optimization techniques identified in Section A.2.4.4. The method enables optimal resource allocation decisions to be identified considering multiple interrelated and/or conflicting objectives. The MODA method can be conducted in a top-down or bottom-up fashion. In a *top-down approach*, program level trade-off analysis is conducted to identify funding levels based on how each asset or program will respond to a given funding level. The responses (i.e. performance) are used to create response curves, showing performance measures as a function of the funding level. Projects are then prioritized based on the level of funding available for that asset and the ability to satisfy the goals identified for that asset or program. In a *bottom-up approach*, a set of projects are selected from potential projects spanning all assets which, maximize the overall measure of performance (i.e. utility). The trade-off analysis is conducted at the project level. Unlike the top-down approach, there are no direct results showing the implications of the level of funding applied to an asset class. This can raise technical challenges associated with developing robust and universal algorithms and the collection of good quality data.

The literature review revealed two methodologies used for cross-asset resource allocation. The first is a framework proposed by Porras-Alvarado et al. (2016). This framework begins with the identification of agency-level goals and objectives and establishes relationships between funding levels and asset condition. The optimization exercise focuses on three objectives: (1) maximizing allocated funds with respect to asset needs, (2) minimizing disparities in equity among different types of assets and (3) maximizing the performance of the system of assets. Accounting for appropriate asset life cycles when determining funding needs can help minimize the potential for under-funding and disparities in equity among different types of assets.

The second methodology, proposed by Fwa and Farhan (2012), begins with the identification of recognized performance metrics for the different asset classes within a system. This approach also establishes the relationships between funding levels and asset condition. The optimization exercise focuses on minimizing disparities in equity among different types of assets, while maintaining the funding necessary for minimum performance levels among each type of asset.

A.3 Implementation of performance-based decision making for asset management

This chapter summarizes the state-of-practice for implementing performance-based decision making for asset management in Canada and the United States. Until now, relatively little recent information has been available on this subject in the Canadian context. Consequently, a survey was conducted as part of this project to fill this critical knowledge gap and three case studies were completed to learn more about current practice in selected Canadian jurisdictions. Results of this survey and the case studies are included in this chapter. In addition, the chapter summarizes recent literature on the state of practice in the United States.

A.3.1 State of practice in Canada

As indicated in Chapter A.1, a total of 53 agencies responded to the online survey regarding performance-based decision making. This section presents the results obtained from the respondents.

A.3.1.1 Extent of use of asset management programs and level of satisfaction

Figure 2 shows the proportion of respondents, for each asset class, that have an asset management program. Pavements are the most common asset class for which an asset management program is in place, with 89% of respondents indicating that they include pavements in their asset management program. Bridges are the second most common asset class with an asset management program with just over three-quarters (77%) of respondents indicating they have a program in place. Few respondents (13%) indicated that they have an asset management program for transit. Other assets identified in the survey as having or being part of an asset management program were airports, ferry facilities, guardrails, building facilities and equipment storage buildings, parks, landfills and rights-of-way (vegetation control and hazards).

Figure 3 shows the level of satisfaction identified by respondents with respect to their various asset management practices and procedures. Half of the respondents with an asset management program in place for pavements (51%) indicated that they are somewhat satisfied with their jurisdiction's current asset management practices and procedures, while 21% are somewhat or very dissatisfied. Similarly, just over half (54%) of respondents indicated that they are somewhat satisfied with their bridge asset management practices and procedures, however, they indicated a lower dissatisfaction level of 12% relative to pavements. Subsurface infrastructure received the highest satisfaction level with 86% of respondents indicating that they are very or somewhat satisfied, followed by bridges at 80%. Culverts and paths and sidewalks received the highest dissatisfaction levels of 26% and 23%, respectively.

Figure 2: Extent of use of asset management programs

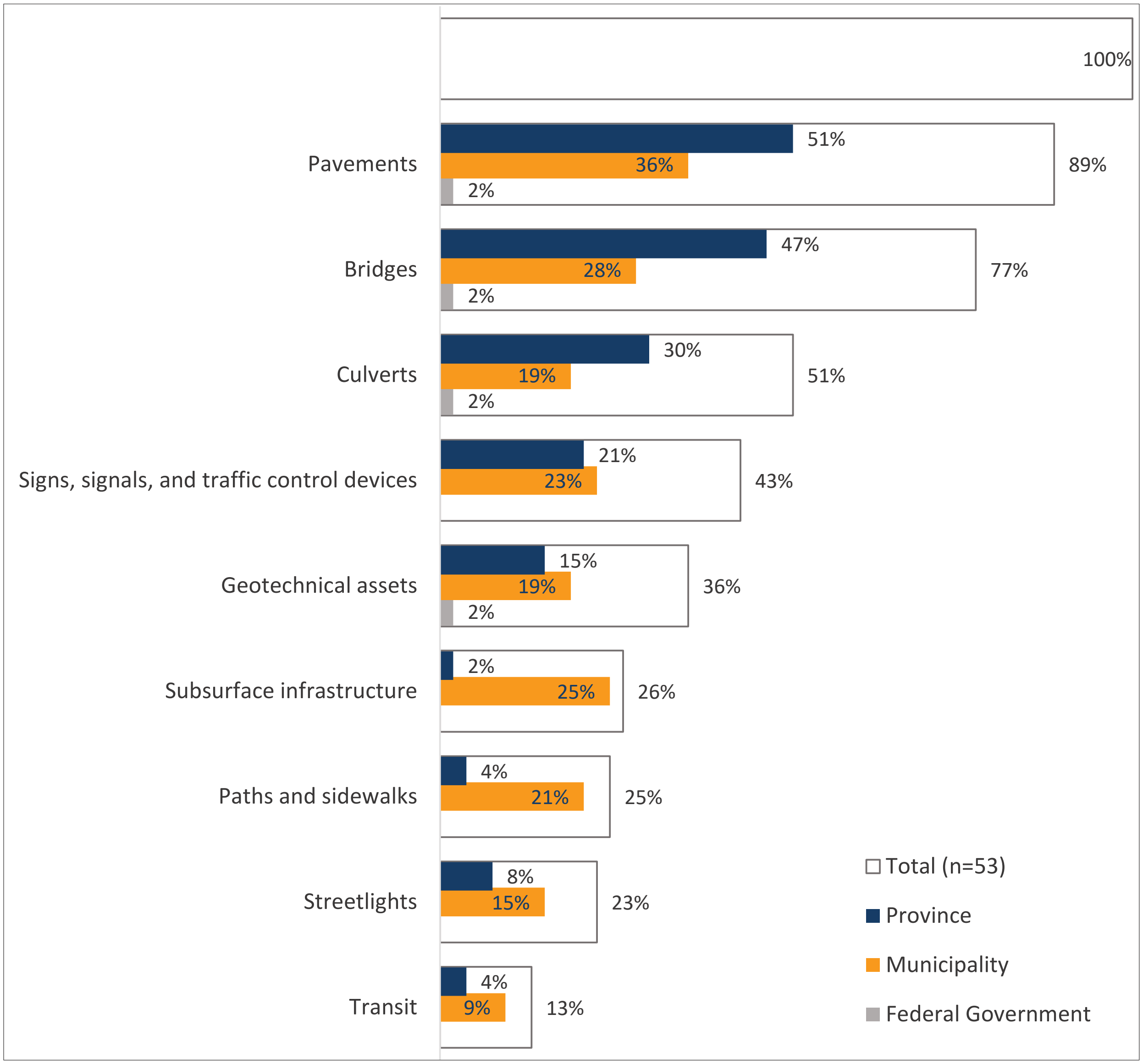


Figure 3: Agency satisfaction with asset management practices and procedures

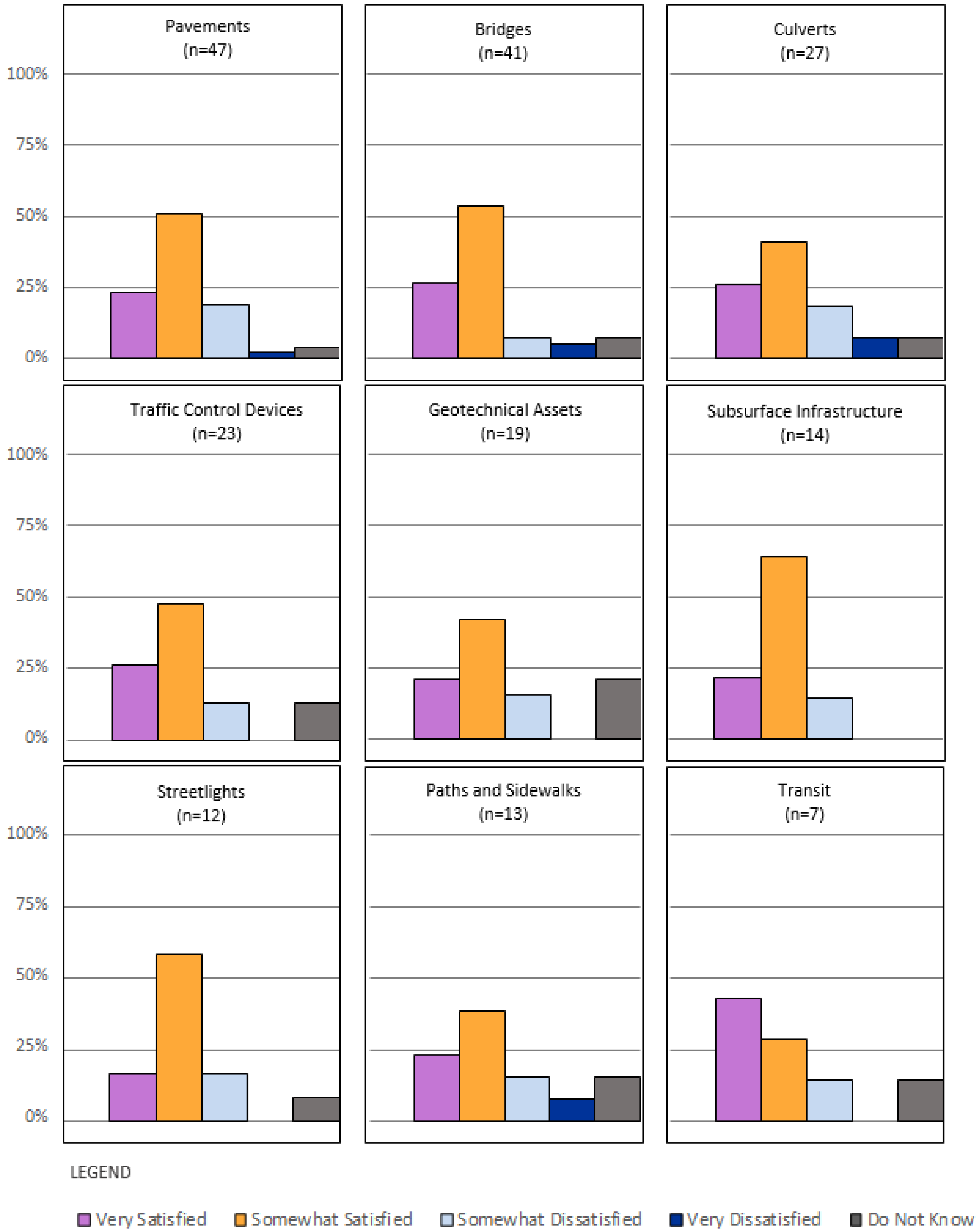


Figure 4 shows the reasons/attributes indicated by respondents with respect to the identified levels of satisfaction stated in Figure 3. The attributes provided to the respondents were:

- Currency (i.e. whether the program is up to date or if progress has been made since the program was implemented)
- Completeness (i.e. whether the program encompasses all required aspects or if some elements remain incomplete)
- Data quantity
- Data quality
- Data availability
- Software capabilities
- Staff turnover
- Institutional knowledge
- Other

Key findings from Figure 4 follow:

- Overall, the asset management programs received a relatively high average satisfaction level in terms of data quantity, data quality and completeness.
- With the exception of bridges, culverts and paths and sidewalks, the asset management programs received a relatively high average satisfaction level in terms of currency.
- Respondents with pavement asset management programs indicated the highest average satisfaction level with data quantity and the lowest average satisfaction level with staff turnover.
- Respondents with bridge asset management programs indicated the highest average satisfaction level with data quantity and completeness and the lowest average satisfaction levels with software capabilities and staff turnover.
- The lowest average satisfaction levels of all assets were identified for paths and sidewalks due to software capabilities, currency and staff turnover. Culverts received the second-lowest average satisfaction levels due to software capabilities and staff turnover.
- Transit received the highest average satisfaction levels with the highest satisfaction score in most attribute categories; however, the number of responses was low.
- Other than transit, the highest average satisfaction levels were received by subsurface infrastructure for currency, geotechnical assets for completeness and traffic control for software capabilities.

Figure 4: Average satisfaction by attribute for each asset class

Note: "n" does not include the respondents that selected "do not know" regarding satisfaction level in Figure 3

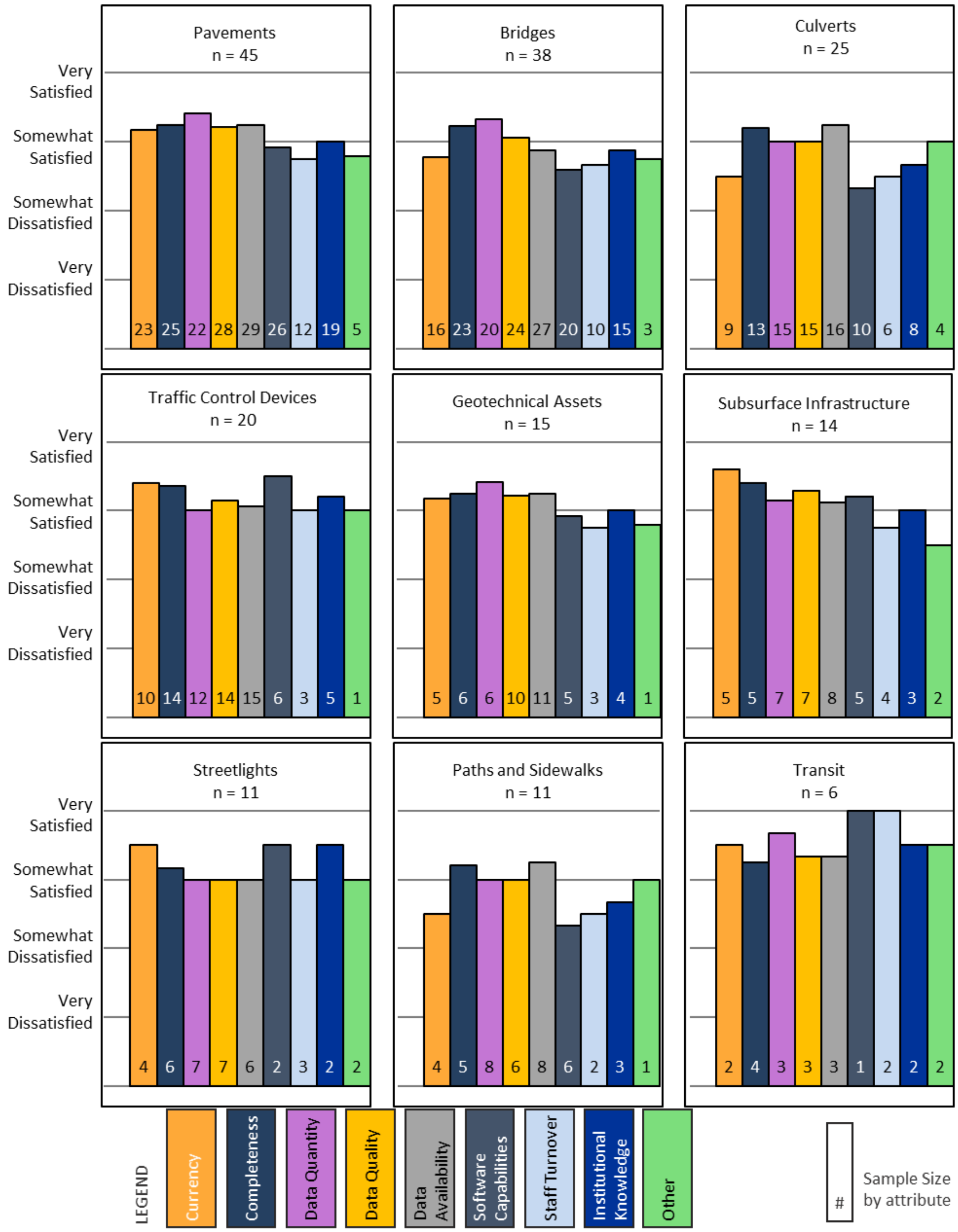


Table 6 shows the non-traditional or intangible asset classes included in the respondents' asset management programs. In most cases (62%) the responding jurisdictions stated that they do not include intangible asset classes in their asset management program. Of the 31 respondents that do include intangible asset classes, data was the most commonly included (52%) non-traditional asset in asset management programs. Other non-traditional or intangible assets specified by respondents were parks, housing, emergency services, systems and virtual equipment, computer software licenses and natural assets.

Table 6: Non-traditional or intangible asset classes included in asset management programs

Non-traditional/intangible asset classes	Number of respondents (n=53)
No intangible assets included in program	33
Data	16
Human capital	7
Other	8

The respondents indicated whether they had implemented cross-asset optimization in their asset management program. Of 51 respondents, 45% do not implement cross-asset optimization in their asset management program, while 24% do. Agencies indicating some level of cross-asset management program included:

- Government of Northwest Territories
- Ontario Ministry of Transportation
- City of Winnipeg
- City of Courtenay
- City of Vaughan
- City of Brantford
- Regional Municipality of York
- Ville de Montréal
- City of Toronto

Jurisdictions/agencies that indicated they have cross-asset management programs in place were asked to identify the combination of assets that are considered together in an asset management program. Figure 5 shows the number and proportion of responding jurisdictions that consider different combinations of assets in an asset management program. The most common combination of asset classes in cross-asset programs are pavements and bridges (42%), pavements and subsurface infrastructure (42%) and bridges and culverts (42%), followed by pavements and culverts (33%) and pavements and paths and sidewalks (33%).

Figure 5: Combination of asset classes in cross-asset programs

	Pavements	Bridges	Culverts	Paths and sidewalks	Transit	Signs, signals, and traffic control devices	Streetlights	Geotechnical assets	Subsurface infrastructure	Other
Pavements										
Bridges	5 (42%)									
Culverts	4 (33%)	5 (42%)								
Paths and sidewalks	4 (33%)	1 (8%)	1 (8%)							
Transit	1 (8%)	1 (8%)	1 (8%)	0 (0%)						
Signs, signals, and traffic control devices	3 (25%)	3 (25%)	3 (25%)	1 (8%)	1 (8%)					
Streetlights	3 (25%)	2 (17%)	2 (17%)	1 (8%)	1 (8%)	3 (25%)				
Geotechnical assets	2 (17%)	2 (17%)	2 (17%)	1 (8%)	1 (8%)	2 (17%)	2 (17%)			
Subsurface infrastructure	5 (42%)	2 (17%)	3 (25%)	2 (17%)	1 (8%)	3 (25%)	3 (25%)	2 (17%)		
Other	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	

Note: The value in each cell represents the number of respondents for each asset class combination. The percentage in brackets is the proportion of total respondents (n=12) that have cross-asset management programs.

A.3.1.2 Tools and techniques for optimization

Table 7 shows the types of tools that the responding jurisdictions use to support their asset management programs. GIS tools are the most commonly used tool with 58% of respondents using them, while off-the-shelf asset management software programs were the least common, with 32% of respondents using them. Some of the commonly specified tools used by the responding jurisdictions (either off-the shelf or tailored) to conduct optimization of asset resource allocation are: Stantec's Highway Pavement Management Application (HPMA) and Bridge Management (BMS) systems, Vemax Suites, dTIMS, MS Access, MS Excel, Geomedia and ArcGIS programs.

Table 7: Tools used to support asset management programs

Tools	Number (%) of respondents (n=53)
GIS tools	31 (58%)
Tailored off-the-shelf asset management software	23 (43%)
In-house asset management software	19 (36%)
Off-the-shelf asset management software	17 (32%)
Other	4 (8%)

Figure 6 shows the optimization techniques that the respondents use for managing assets. Engineering judgement was identified as the most commonly used optimization technique for asset management

(68%), followed by level-of-service targets (60%) and risk exposure analysis (58%). The least common technique identified was the internal rate of return on investment (15%).

Figure 6: Optimization techniques used for managing assets

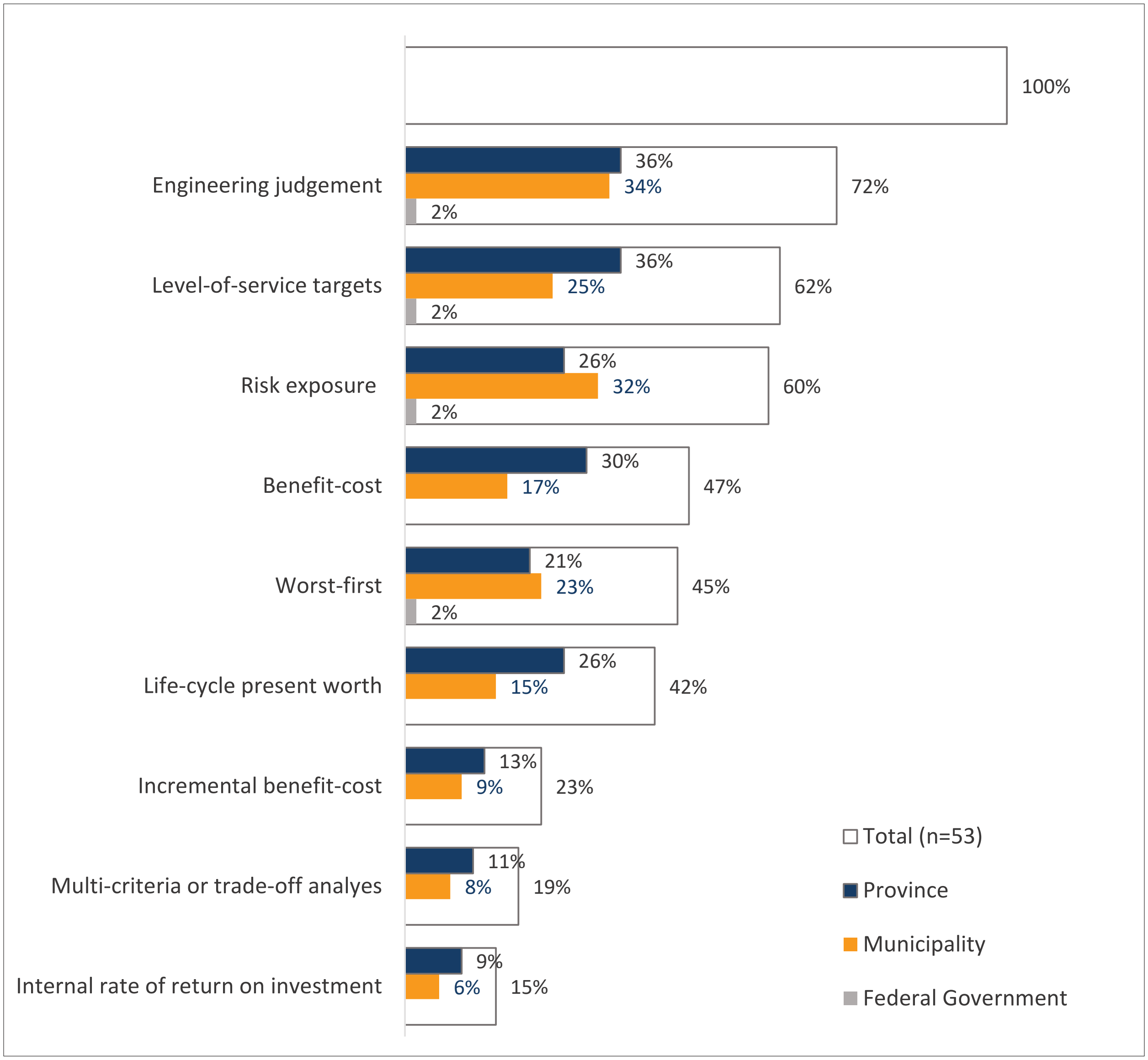
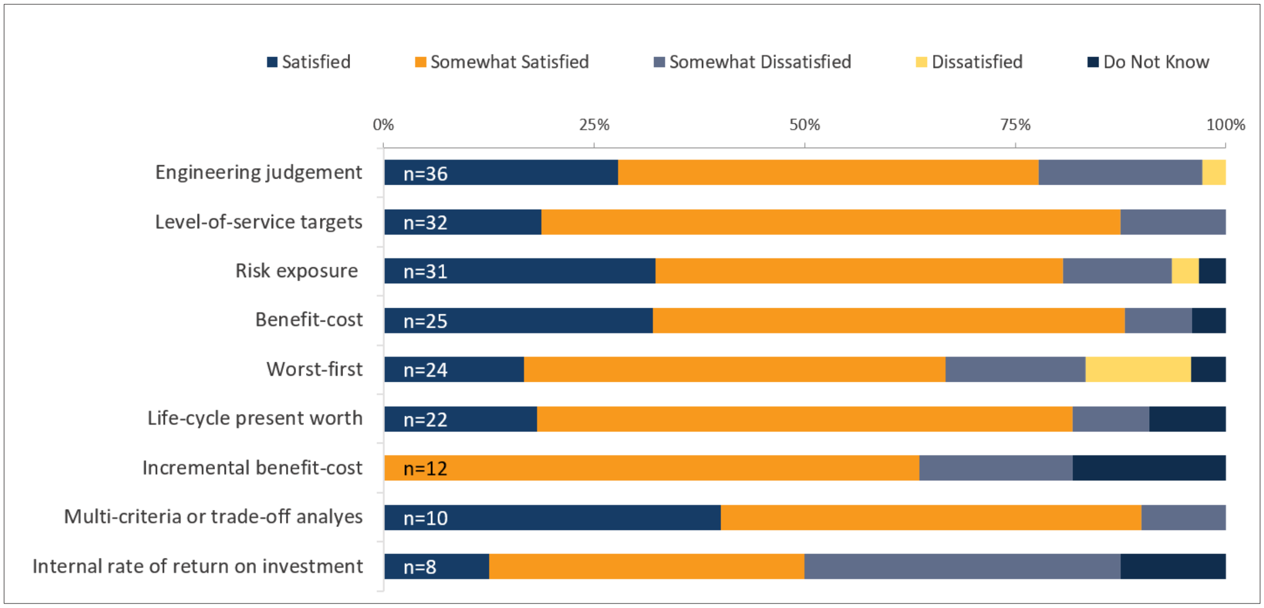


Figure 7 shows the level of satisfaction identified by respondents with respect to the asset management optimization techniques in Figure 6. Although the multi-criteria or trade-off analysis technique was identified as being implemented by a relatively low number of respondents, it received the highest satisfaction level, with 40% of those that use the method indicating that they are very satisfied and 50% indicating that they are somewhat satisfied. Level of service targets and benefit-cost optimization techniques received the second-highest satisfaction levels (88% of respondents either very or somewhat satisfied with each); however, the level-of-service targets technique received a slightly higher dissatisfaction level than the benefit-cost technique (with 13% versus 8% indicating they were somewhat dissatisfied).

Figure 7: Level of satisfaction with asset management optimization techniques



The internal rate of return on investment optimization technique received the lowest satisfaction level by responding jurisdictions, with 38% of respondents indicating that they are somewhat dissatisfied. The worst-first optimization technique received the second-lowest satisfaction level, with 13% of respondents indicating that they are very dissatisfied and 17% indicating that they are somewhat dissatisfied.

A.3.1.3 Asset management and performance-based frameworks

Among responding jurisdictions/agencies, 38% indicated their asset management program is part of a broader performance-based framework, 25% stated it is not and 38% did not know.

Figure 8 shows the level of impact that various performance objectives were indicated to have on agencies' asset management decisions. The performance objective that was commonly identified by respondents as having the highest level of impact was asset condition, followed by safety. Environmental sustainability and liveability were identified as having the least impact on asset management decisions.

Table 8 shows the types of performance measurements included in asset management programs:

- Infrastructure condition
- Program outputs, defined as the scale of activity performed (e.g. kilometres of paved roads, percent deficient bridges)
- Program inputs, defined as the resources used (e.g. dollars invested, personnel and equipment)
- Program outcomes, defined as the degree of success in achieving objectives (e.g. level of service, level of safety, reduction in emissions, liveability)

The most common performance measure type identified by the respondents was infrastructure condition (77%), followed by program outputs (70%). The least common performance measurement was program outcomes (49%).

Figure 8: Level of impact each performance objective has on asset management decisions

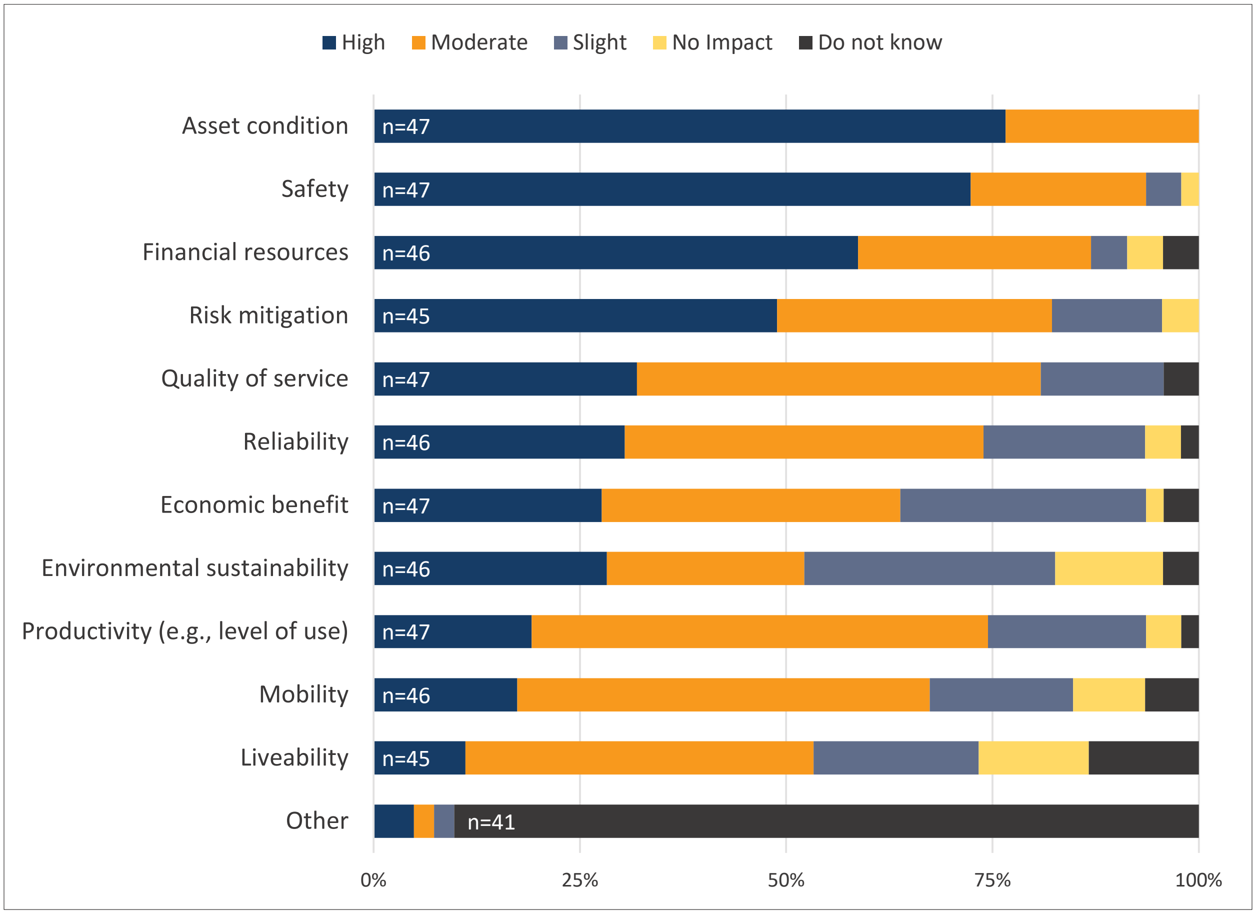
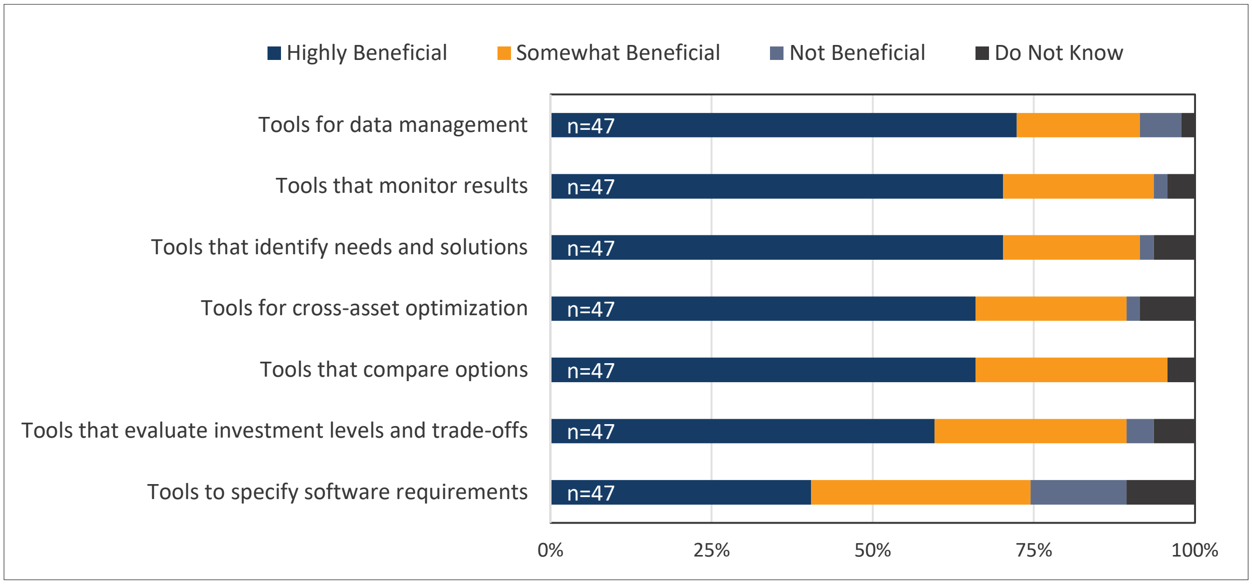


Table 8: Performance measure types measured by agencies

Performance measure types	Number of respondents (n=53)
Infrastructure condition	41 (77%)
Program outputs	37 (70%)
Program inputs	29 (55%)
Program outcomes	26 (49%)
Do not know	2 (4%)

Figure 9 shows the extent to which various tools would be beneficial to the responding agency for performance-based decision making. Respondents stated that tools for data management would be the most beneficial, followed by tools that monitor results. Tools for specifying software requirements were identified as the least beneficial.

Figure 9: How beneficial different tools are for performance-based decision making



A.3.1.4 Summary of findings from jurisdictional survey

Responses to the jurisdictional survey revealed the following key findings:

- Thirty-eight percent of agencies said their asset management program is part of a broader performance-based framework. However, the same number said they did not know if it was.
- Cross-asset optimization is implemented in about a quarter (24%) of asset management programs. The most common combination of asset classes in cross-asset programs were pavements and bridges (42%), pavements and subsurface infrastructure (42%), bridges and culverts (42%).
- The key performance objectives in existing asset management programs were asset condition and safety.
- Engineering judgement was identified as the most commonly used optimization technique for asset management (68%), followed by level-of-service targets (60%) and risk exposure analysis (58%). Level-of-service targets received a relatively high satisfaction level, with 19% of respondents indicating that they were very satisfied and most respondents (69%) indicating that they were somewhat satisfied. Risk exposure analysis also received a relatively high satisfaction level, with 32% of respondents indicating that they were very satisfied and 48% indicating that they were somewhat satisfied. Although the multi-criteria optimization (or trade-off analysis) technique was identified as being implemented by a relatively low number of respondents, it received the highest satisfaction level, with 40% of those that use the method indicating that they were very satisfied and 50% indicating that they were somewhat satisfied.
- Respondents identified tools for data management and tools that monitor results as being most beneficial for performance-based asset management programs.
- The most commonly stated challenges identified by participating agencies regarding allocation of available financial resources to transportation infrastructure asset management were:
  - Limited available staff time and contractor resources to develop, operate and maintain a program as well as limited budget and resources for required staffing

- Ensuring a robust and consistent understanding of all asset needs for maintenance, growth and expansion (i.e. creating an inventory of assets and assessment of conditions)
- Consistency and timely program delivery due to inadequate funding and staffing; delays in implementing preservation treatments for the right asset at the right time lead to accelerated deterioration that result in costlier treatments
- Complexity of technology and the need for expertise other than civil engineering
- Extreme weather and geotechnical (permafrost) condition
- A well-established cross-asset allocation method that optimizes investments across various asset classes in the whole transportation system
- Lack of best practice asset management for other assets besides pavements and structures (e.g. rest areas, truck inspection stations, ferry services, remote airports, illumination, guardrails, median barriers, traffic signals, signs, salt domes, patrol yards)
- Moving towards a more service-oriented asset management approach versus the older traditional asset-centric model that includes a multimodal and active/mass transportation perspective
- Institutional challenges such as the procurement process for software programs and changing plans for infrastructure investments
- Political pressures for other capital infrastructure
- Lack of leadership and understanding from senior decision makers regarding the value of an asset management program

A.3.2 Case studies

Three case studies were conducted to show examples of current applications regarding the following: (1) cross-asset optimization; (2) development and implementation of a performance-based asset management program; (3) resource allocation within a transit agency; and (4) pavement management. The agencies selected for these case studies are the Regional Municipality of York, TransLink (South Coast British Columbia Transportation Authority) and Saskatchewan Ministry of Highways.

In compiling these case studies, the project team relied on information that was provided by each agency, as well as interviews with agency staff. In some instances, confidential information was shared with the authors with the sole purpose of establishing context for the case study; these details could not be included as part of the case study discussions. For example, the Regional Municipality of York has spent extensive time and resources developing a comprehensive risk-based framework to assess the investment needs of various assets, particularly for cross-asset optimization. However, at the time of publication, details associated with this framework were not ready to be shared with the public. As such, the case study refers to the framework and provides a high-level discussion about it but does not address specific issues.

As a second example, TransLink recently developed a comprehensive corporate asset management strategy, which assists them with the evaluation and prioritization of projects for funding allocation. While the case study discusses the components of the strategy, it does not provide details about the criteria, mechanisms or analysis tools used in the operation of the decision support tool that objectively evaluates investment options. These details were provided confidentially to the authors to assist with the overall understanding of the process and how various components fit together.

A.3.2.1 Regional Municipality of York

This case study illustrates the current approach followed by the Regional Municipality of York for asset management, including cross-asset optimization and key lessons learned in the development and implementation of a performance-based asset management program. This approach is expanding across Regional departments and is continuously evolving as the Region's asset management program matures. The information for this case study was obtained from interviews with Regional staff, material shared by the Region and the Council-approved *2018 Corporate Asset Management Plan (CAMP)*[2].

Overview

York Region is one of the fastest growing regions in Canada. It includes nine municipalities ranging from large urban centres to smaller rural towns: Aurora, East Gwillimbury, Georgina, King, Markham, Newmarket, Richmond Hill, Vaughan and Whitchurch-Stouffville (Figure 10). The Region is forecasted to have 1,790,000 residents and 900,000 jobs by 2041.

The Region operates a comprehensive asset management program that encompasses 13 service areas as shown in Table 9, plus YorkNet, the Region's telecom network. For each of these areas, the Region tracks information on the state of its infrastructure, including an asset inventory, average asset life, asset condition and the replacement value for both core and non-core assets. Core assets represent more than 75% of all physical assets in the Region and include roads, bridges, culverts and those used for water, wastewater and stormwater management.

As per Ontario Reg 588/17 *Asset Management Planning for Municipal Infrastructure*, which went into effect on January 2018, the Region must identify the level of service of its core assets by July 2021. The same regulation requires the Region to report its level of service for all assets (core and non-core) by July 2024.

[2] The plan can be accessed at https://www.york.ca/wps/wcm/connect/yorkpublic/2547467d-711b-482e-8602-0456b02bc96a/may+3+corporate+ex.pdf?MOD=AJPERES).

Figure 10: York Region

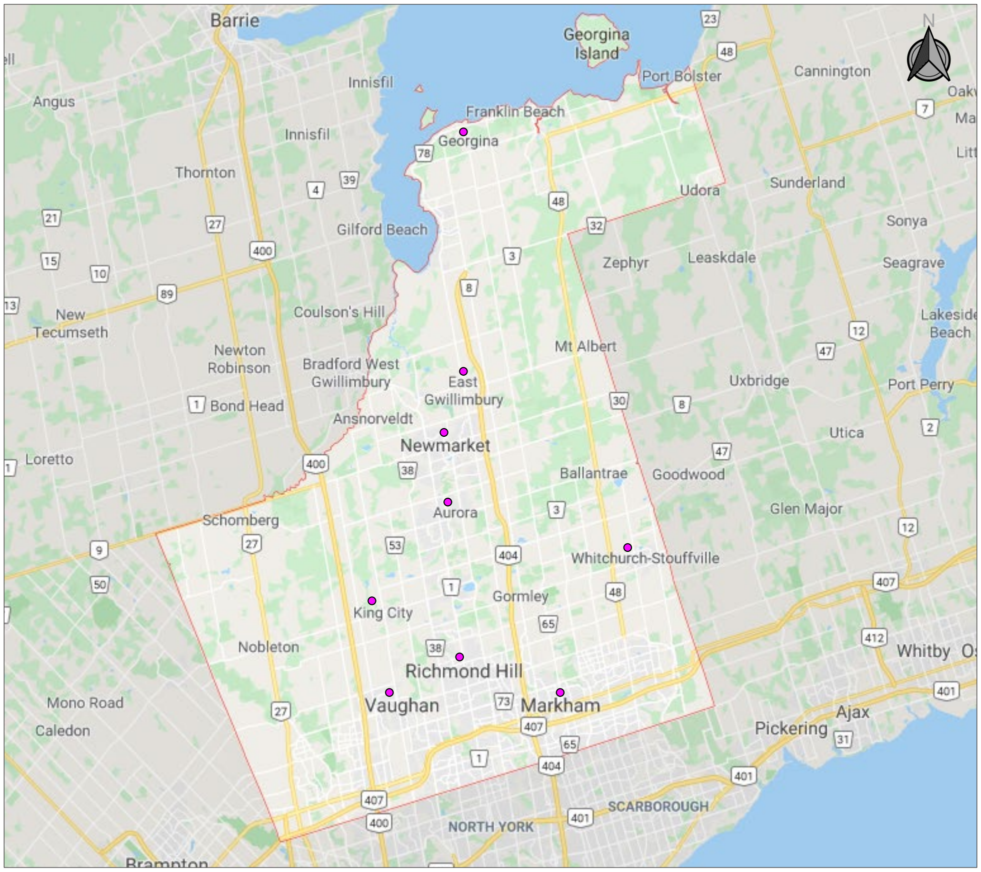


Table 9: Service areas in York Region's corporate asset management plan[3]

Service group	Service area
Community and Health Services	Housing services Paramedic services Senior services
Corporate Management (includes Finance and Corporate Services)	Information technology Property services
Environmental Services	Energy management Forestry Waste management Wastewater (core asset) Water (core asset)
Transportation Services	Roads (core asset) Transit
York Regional Police	Police services

[3] York Region (2018), *Corporate Asset Management Plan*.

In the *Roads* service area of the *Transportation Services* group, the Region includes the following assets: paved roads in urban and rural environments including stormwater infrastructure, bridges, culverts traffic signals, roadside assets, road maintenance facilities, vehicles and equipment and service area support vehicles. In its 2018 *Corporate Asset Management Plan*, the Region identified the extent of the *Roads* service area as follows:

- 4,028 lane-kilometres of urban and rural Regional roads
- 152 bridges
- 165 culverts (span more than 3.0 metres)
- 41 retaining walls (height more than 2.0 metres)
- 30,000+ traffic signs
- 5.8 kilometres of noise barriers
- 4 buildings (patrol district facilities)
- 299 vehicles and equipment

The Region's asset management program has significantly evolved since 2016, during which time the Region has invested extensive resources to enhance data collection. As a result, there have been significant improvements in the quality and quantity of data available to operate the system, resulting in current and complete information that can be used for objective and transparent analysis.

In 2006, York Regional Council introduced a policy to allocate funds into reserves for future rehabilitation and replacement of core assets. Before 2013, the annual increase in the Region's contribution to asset replacement reserves was 1% of the prior year's tax levy. That year, Council approved a new policy to increase the annual incremental contribution by a further 0.2% per year until it reached 2% of the prior year's tax levy in 2017. With that policy direction achieved, the contributions in the 2018 budget represented an increase of 4.2% from the previous year. In addition, 100% of the Region's supplementary tax revenues may be added to these reserves each year, as per Council policy.

Asset management policy and framework

York Region Council first adopted a Corporate Asset Management Policy in 2013 to support the Region's asset management programs and provide a framework to ensure long-term asset sustainability and demonstrate fiscal stewardship for the Region's assets. In 2018, the Ontario provincial government enacted Regulation 588/17 *Asset Management Planning for Municipal Infrastructure*, which is intended to provide certainty for future provincial asset management planning requirements and support asset sustainability. This prompted the Region to update its Corporate Asset Management Policy to align with the new regulation while advancing their asset management practices. Key updates to the Policy include[4]:

- Illustrating the critical connection between corporate strategic direction (e.g. Vision 2051, Strategic Plan and Fiscal Strategy) and the Asset Management Strategy
- Identifying departmental asset management leads who coordinate with Finance to deliver financially sustainable departmental asset management programs

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[4] York Region (2018), Update to Corporate Asset Management Policy, https://www.york.ca/wps/wcm/connect/yorkpublic/447eacf4-951b-4bb5-aad4-52ffd8cd47e8/feb+1+update+ex.pdf?MOD=AJPERES&CVID=mu8swKf

- Recognizing the benefits of making evidence-based decisions based on life cycle data to maximize the value obtained from assets
- Highlighting the importance of service delivery and incorporating expectations from customers, including local municipalities, residents and businesses and Regional departments
- Aligning asset management planning with climate change mitigation approaches, such as greenhouse gas emission (GHG) reduction goals and targets, in parallel with the Region's Climate Change Action Plan
- Integrating asset management industry standards and best practices, including ISO 55000 to drive continuous improvement and manage asset-related cost, performance and risk

The resulting asset management program is part of a broader performance-based framework for resource allocation. Under this framework, clear objectives for asset management practices across all Regional departments ensures a consistent, coordinated and affordable approach to providing services. The following objectives are provided in this framework[5]:

- Adopt and advance industry-leading asset management practices that align with established standards and legislation
- Provide defined levels of service which are balanced against considerations of costs and risks
- Align Asset Management Plans with the Regional Fiscal Strategy
- Demonstrate financially sustainable life cycle management by appropriately balancing cost, risk and performance to achieve full value from assets
- Improve evidence-based decision making from in-service asset data related to expenditures, operations and maintenance
- Ensure organizational accountability and transparency by engaging users to provide input into asset management planning

This performance-based framework was created in 2010 due to observed declines in the performance of existing assets and the need for better decision making regarding funding allocation of the asset replacement reserve. As part of a performance-based system, resource allocation is determined using evaluations based on service value. Each department also reports on the performance of various assets on an annual basis using key performance indicators (KPIs) that have been selected by the organization. There are cases, however, where political input also plays a role in resource allocation.

Level of service and risk analysis

The Region measures the level of service (LOS) of core infrastructure based on community and technical input, as required by regulation. Community levels of service are outlined at a corporate level through strategic objectives and key performance indicators established in the Region's Strategic Plan. For example, a key strategic objective in the Plan is "Managing the Region's assets for current and future generations," and one corresponding performance measure is to "Maintain % of regional assets with a condition assessment rating of fair or better condition."

Each of the service areas identified in Table 9 is assigned a grade, based on the following three criteria:

- *Reliability* refers to the quality of service the infrastructure delivers based on regulatory standards, risk, health and safety and security

[5] York Region (2018), *Corporate Asset Management Plan.*

- *Capacity* measures the capacity available to meet servicing needs based on current and projected demand over time
- *Condition* refers to the physical condition of the infrastructure, based on observed damage and deterioration with age and use

Table 10 shows the condition grading system resulting from the application of these criteria[6].

Table 10: York Region's condition grading system

Grade	Description	Condition criteria	Criteria description
VG	Very Good	Fit for the future	Well maintained, good condition, new or recently rehabilitated
G	Good	Adequate for now	Acceptable, generally approaching mid-stage of expected service life
F	Fair	Requires attention	Signs of deterioration, some elements exhibit deficiencies
P	Poor	Increasing potential of affecting service	Approaching end of service life, below standard, significant deterioration
VP	Very Poor	Unfit for sustained service	Near or past service life, advanced deterioration, assets may be unusable

Table 11 shows the performance of the *Roads* service area under two of the three criteria, by specific measures required by O.Reg.588/17. The reference source did not include similar information regarding reliability as it pertains to *Roads*.

Figure 11 illustrates the condition grade of Regional core assets[7]. As the figure illustrates, 6% of core assets have been classified as being in poor or very poor condition. These types of assets would typically be included in the 10-year capital renewal program and budget forecasts identified in the Region's *Corporate Asset Management Plan*. However, as it pertains to road infrastructure, there is a significant shortfall between available funding and the renewal requirement, which results in a more pressing need for more evidence-based resource allocation.

[6] York Region (2018), *Corporate Asset Management Plan*.

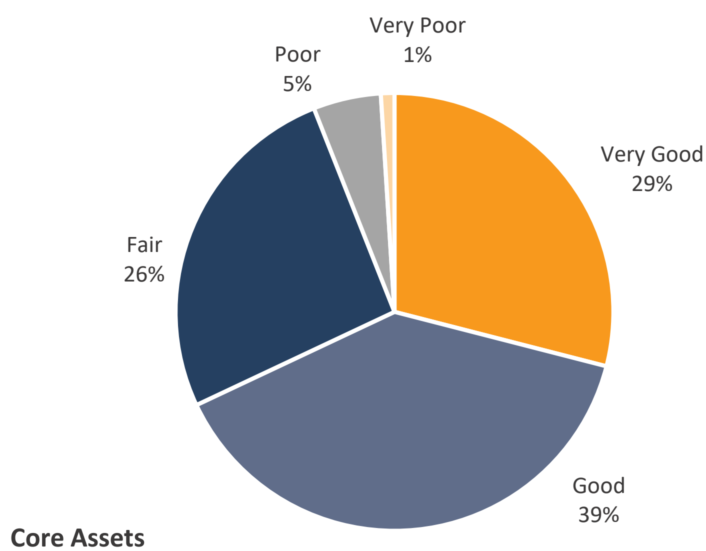
[7] Ibid.

Table 11: Performance of roads service area by regional criteria

Level of service indicator	2016 actual	Discussion on gaps and trends
CAPACITY		
Number of lane-km of arterial roads per land area (km/km^2)	1.7%	There is currently a need for $1.329 billion in road traffic capacity improvement works as planned in the 10-Year Roads Capital Plan.
Number of lane-km of collector roads per land area (km/km^2)	0.6%	
Percent of bridges with loading or dimensional restrictions	0%	
RELIABILITY		
No information available for 'Roads'		
CONDITION		
For paved roads, average pavement condition index (PCI)	70.0	There is currently a $350 million backlog in pavement and associated road renewal works, of $58 million in structures renewal work and $74 million in storm pipes, roadside ditches and small culverts.
For bridges, average bridge condition index (BCI)	74.7	
For structural culverts, average bridge condition index (BCI)	71.7	

Source: Extracted from York Region (2018) Corporate Asset Management Plan

Figure 11: Condition grade of York Region assets



Since assets deteriorate at different rates and lose the ability to deliver the required levels of service, the Region has developed asset renewal strategies to identify the frequency and cost of activities that provide defined levels of service, at the best life-cycle cost. These renewal strategies vary in their complexity, from straightforward asset replacement at the end of the asset's useful life (as is the case with low-cost assets such as information technology equipment), too much more complex scenarios where an asset (e.g. bridges, pavements) requires rehabilitation numerous times throughout its life. For Regional roads, renewal planning is supported by the Region's pavement management system, which helps to forecast short and medium-term needs and priorities based on road inspection data collected every two years.

The Region conducts biennial pavement inspections to determine how the driving surface of the road is performing. Based on these inspections, resurfacing treatments are performed as necessary.

The Region has also implemented 100-year life cycle models for all asset categories and compares them based on risk analysis and available funding. This approach requires a high degree of specialization and knowledge about the topic. Notably, it has taken the Region 13 years to get to this point in terms of knowledge and success.

Cross-asset optimization

As stated in the Region's *Corporate Asset Management Plan*, "the goal of asset management is to deliver required performance at the best possible cost over an asset's life cycle within an acceptable level of risk." To that end, the Region develops estimates of the replacement value, condition and remaining life of assets to inform decisions regarding asset renewals and reduce the risk of service disruption. Condition assessment programs assist in determining the rate of deterioration of various assets over time, including forecasts of future conditions and help to inform the most beneficial type and timing of treatment.

The Region inspects assets using the condition grading system discussed in the previous section. These inspections are done on schedules that are appropriate to the asset group, with more critical assets (e.g. bridges and structural culverts) inspected more frequently than less critical ones. Critical assets in poor or very poor condition receive increased attention and renewal investment to avoid higher maintenance costs and/or unexpected failure. These assets are a priority for inclusion in 10-year capital renewal programs and budgets.

Asset condition monitoring is increasingly being done through the use of technology and innovation, for example, robotic inspection tools, automated pavement assessment tools, remotely-operated cameras and sensors and mobile data collection devices.

The Region is still in its planning and implementation phase for cross-asset optimization, which is currently being done for selected core asset classes, using the following optimization methods: level of service targets, life-cycle present worth, benefit-cost analysis and risk exposure. The Region is working to include all assets in these methods. The Region has selected these methods based on extensive internal research regarding their performance as well as lessons learned from other jurisdictions, mainly in the United States. Each asset is optimized individually and resulting information is entered into a GIS platform that contains details about each asset, including asset condition and other attributes such as age, location, level of service and others. Cross-asset optimization is then completed within the GIS platform, taking into consideration elements that will result in a high return on investment (e.g. combinations of assets that are a high priority based on their existing condition receive preference over other asset combinations).

In addition to the geospatial analysis, the Region also uses engineering judgement as part of the cross-asset optimization process. This is done in a workshop setting that involves all asset management team leaders, who may develop additional scenarios for the geospatial analysis for which certain assets may be accelerated and others delayed for optimization based on available funding. For example, if there is an area where a watermain needs maintenance in five years, a road (pavement) needs maintenance in seven years and a storm sewer in 10 years, the team may use this as a scenario for maintenance consideration to optimize available funding and reduce risk.

Because the Region understands that risk-based asset management is important, the Region is currently working on a comprehensive risk-based framework to assess investment needs of various assets and it is expected that the accompanying technical models will be ready for application in 2020. This framework will largely replace the current approach to cross-asset optimization.

Lessons learned

York Region has demonstrated over the last 14 years that designing, developing and implementing a performance-based asset management program takes vision and good leadership, collaboration and commitment. The following discussion highlights key drivers behind the success of the Region's program.

Vision and leadership

- In 2006, Council had the foresight to create a special reserve fund with an annual investment equal to 1% of the prior year's tax levy for the purposes of future asset management.
- In 2010, the Region created a dedicated asset management team that has grown from one to 12 people in the transportation area alone.
- In 2013, the first asset management strategy was created to serve as a guideline for asset management in the Region. This strategy provided the vision for everything else that followed and helped create a culture of asset management within the workplace, as well as a sense of empowerment and ownership within the asset management team. The Corporate Asset Management Policy was adopted by Council in 2013 and updated in 2018.
- In 2018, permanent full-time staff were hired to form a permanent Corporate Asset Management Team providing oversight, coordination and guidance to the now 14 service areas, as well as to establish lines of communication between service areas and senior management teams.
- Asset management plans were initially developed in 2016 for each asset class.

Collaboration

- Collaboration has been critical to ensuring the success of the Region's asset management program. In 2013, the Region created the Corporate Asset Management Steering Committee and Coordinating Committee. These committees were created to develop the policy and framework for the asset management groups and to ensure York Region was investing wisely in their assets. While at first, these committees were mainly from transportation and environmental services groups, the group now has grown to include staff from other support areas (e.g. finance, accounting, legal, emergency services) and all service areas.

- Collaboration includes working closely with elected officials who are supportive of evidence-based decision making. This is important because when elected officials support an idea, they support senior management and overall success follows.

Commitment

- The Region has been working on their asset management program for nearly 14 years. This speaks to the importance of long-term planning and commitment. The Region understands that asset management is intergenerational and requires time and effort.
- Another type of commitment is to the incorporation of new ideas and concepts that will advance the program. Until 2014, the municipality did not include any intangible asset classes (e.g. data) in its asset management program. However, in the last two years, the municipality has made a significant investment in data collection and maintenance. The driver behind this is that high quality data is now perceived as being the Region's most important asset since, in their opinion, infrastructure investment cannot happen without access to good quality data. As such, Council has approved the inclusion of data as another asset in the system. The municipality is currently evaluating the replacement value of the data they own and will be developing their first asset management plan for data in 2020, together with the asset management plans for all other asset classes.
- The Region has invested in software (e.g. Cityworks, a GIS-centric asset management tool that the municipality has customized for better system performance and which is complemented by a pavement management system and a bridge management system and GIS software and feature manipulation engine (FME) for GIS data processing and integration tasks) and data collection hardware, including mobile data collection with tablets and apps. In addition, investment in data analytics and visualization tools, dashboard tools, mapping and asset life cycle/analytical tools have helped improve the program.
- The Region has committed to investing in GIS technical knowledge and, as a result, one-half of the asset management staff in the transportation group are GIS technologists.
- The Region provides specialized asset management training for staff. Everyone has received the Institute of Asset Management training to ensure their skills are up to date with best practices. The next step is to start providing special training to the GIS staff.

A.3.2.2 TransLink (South Coast British Columbia Transportation Authority)

This case study discusses the asset management program of TransLink (South Coast British Columbia Transportation Authority), which was launched in August 2015 and has proven successful in meeting corporate priorities regarding asset management investment decisions. The information for this case study was obtained from interviews with TransLink staff and material shared by TransLink.

Overview

TransLink is Metro Vancouver's regional transportation authority. It is responsible for planning, financing and managing transportation modes and services in the Metro Vancouver region of British Columbia for the safe and efficient movement of goods and people.

TransLink operates and maintains regional transit service and infrastructure with the assistance of subsidiaries and contractors. In addition, the agency owns and maintains five of the region's bridges and shares responsibility for major regional roads and walking and cycling infrastructure with municipalities in the Metro Vancouver region. This is a unique model in that TransLink is the first transportation authority in North America to be responsible for planning, financing and managing all public transit in addition to major regional roads, bridges and cycling infrastructure.

Because of its position as a transportation authority that works in partnership with regional municipalities, TransLink has a unique approach for improving its asset management capability. Each of TransLink's companies and subsidiaries operate and maintain their assets through their own asset management programs and TransLink cost-shares with municipalities to maintain roads and bridges in the region's main road network. As a result of this structure, TransLink's asset management program is not designed to address day-to-day operations but rather to provide stewardship and strategic asset management for the region. This includes providing the value assessment framework for the entire organization.

In 2015, TransLink initiated a multi-year program to improve their asset management practices with respect to investment prioritization across the enterprise. This resulted in the creation of the Capital Asset Prioritization and Investment Tool for Advanced Lifecycle Management (CAPITAL-M), which was rebranded the Corporate Asset Management Strategy (CAMS) in 2019 and is the focus of this case study.

TransLink's Corporate Asset Management Strategy was launched in 2015 with the goal to proactively align TransLink's asset management activities with best practice to serve TransLink's corporate priorities of ensuring a state of good repair of the agency's assets, mobilizing the Mayor's vision and enhancing customer experience. A key driver for this strategy was the Mayor's Council on Regional Transportation's 10-year investment plan (the 10-year vision), since this is now what drives asset management investment decisions at TransLink.

The vision[8]

As the demand for public transportation continued to grow as a result of Metro Vancouver's population growth, the Mayors' Council on Regional Transportation decided in 2014 to develop a 10-year vision for Metro Vancouver's transit and transportation systems. The vision outlines actions and policies to advance the goals identified in TransLink's Long-term Regional Transportation Strategy (i.e. a region that is vibrant and sustainable, a region where people and businesses prosper and a region where the air is clean and the land and people are healthy[9]) and to support the goals identified in Metro Vancouver's Regional Growth Strategy (i.e. create a compact urban area, support a sustainable economy, protect the environment and respond to climate change impacts, develop complete communities and support sustainable transportation choices[10]). This is now the blueprint that guides the preparation of TransLink's investment plans, which are to identify capital and operating expenditures over the next 10 years, as well as how those expenditures will be funded from established revenue sources. TransLink is required to update these investment plans at least every three years.

[8] TransLink (2017), Update to Phase One of the 10-Year Vision: 2017-2026 Investment Plan.
[9] TransLink (2013), Regional Transportation Strategy: Strategic Framework.
[10] Metro Vancouver (2017), Metro Vancouver 2040 Shaping Our Future: Regional Growth Strategy. Adopted in 2011 and updated in 2017).

Corporate priorities and funding allocation

Three corporate priorities drive initial investment decisions:

- Mobilize the Mayors' vision
- Ensure a state of good repair of the agency's assets
- Enhance customer experience

The following guiding principles for transportation investment for part of the decision-making process:

- System expansion should not occur at the expense of maintaining existing or future system performance and the ongoing state of good repair of infrastructure.
- Transportation projects will undergo a rigorous alternatives review including full life-cycle cost analysis prior to approval.
- Capital projects expanding or improving the network will be evaluated on impacts to the overall network's ability to move goods and people and support land use objectives.
- Collaboration should exist between TransLink, the Province and Metro Vancouver to ensure alignment with the Regional Growth Strategy and the stated outcomes of regional transportation funding and investment.

Initial funding is allocated to the set of projects and programs which have been publicly announced as part of the business plan for the year. The remaining funding is forecasted based on the long-term investment plans and updated requirements identified by the operating subsidiaries. The 2019 business plan identifies the details shown in Table 12 for the first two corporate priorities[11]. In general, the planning for the 30-year Transportation Strategy and 10-year Investment Plans are led by the Strategic Planning and Policy (SP&P) team. Their source of their information (available through the Finance Department) is the long-term (15-year) capital plan and on-going operating budgets for TransLink's key subsidiaries (i.e. bus, rail, police, corporate and roads and bridges). The SP&P team evaluate the transportation requirements for the region and relay that information back to the subsidiaries to ensure that forecasted service requirements can be delivered. This is the basis for the list of projects and initiatives shown in Table 12.

The development of annual capital plans and review of the long-term plans are led by the subsidiaries, divided by Capital Working Group (CWG). Although the subsidiaries are primarily focused on ensuring that their state of good repair needs are addressed, they also need to account for the projects and initiatives identified in the Investment Plans and also include their prioritization of projects (supported by the decision support tool valuation) and relevant constraints such as resources, project maturity and others. The CWGs then provide their capital plan, as well as their operating budget requirements to the Finance Department, which in turn confirms affordability based on cash-flows, debt servicing ratios, revenue streams and others. The list of priorities is then sent forward for approvals.

[11] Extracted from TransLink 2019 Business Plan – Operating and Capital Budget Summary

Table 12: TransLink's components of corporate priorities for 2019

Priority One: Implement the Mayors' vision
• Implement four new Rapid-Service B-Line routes including: 41st Avenue, Fraser Highway, Lougheed Highway and North Shore Marine Drive-Main Corridor • Receive and commission the third new SeaBus vessel as well as 178 new conventional buses aimed to replace existing again fleet and expand service • Recruit and train transit operators and support staff to support the expanded service levels • Test, commission and deliver 56 new Mark III rail cars • Modernize the Expo and Millennium Lines infrastructure to increase capacity and accommodate growth • Provide technical support for the design of the Millennium Line Broadway Extension • Construct new bus exchanges at Guildford
Priority Two: Maintain a state of good repair
• Support the replacement of the Transit Management and Communications (TMAC) bus radio system and supporting technology • Implement the 8,000-kilometre internal Preventative Maintenance program at BCRTC in accordance with Commercial Vehicle Safety Enforcement requirements • Install new fareboxes on Community Shuttle fleet • Implement a formal asset management plan and transform the safety management system at British Columbia Rapid Transit Company Ltd. (BCRTC) • Develop and implement an Emergency Response Plan through the IT Disaster Recovery Program • Complete SkyTrain Noise Assessment Study and develop an implementation plan • Upgrade existing infrastructure and conduct ongoing preventative and corrective maintenance of bridges • Implement a formal Safety Management System at TransLink Corporate • Implement a Health and Safety Software system across the enterprise

Corporate asset management strategy

This strategy exists to support the 10-year state of good repair investment priority. It was created to provide justifiable, data-driven investment decisions that take into consideration the long-term asset renewal needs and align with industry standards.

The long-term focus of the CAMS is to serve as an asset management support function that applies leading practices in asset management in a way that ensures alignment across TransLink in a consistent, coordinated and sustainable approach. The key components of the CAMS are shown in Figure 12.

Figure 12: Key elements of TransLink's Corporate Asset Management Strategy[12]

Asset Management Strategy and Objectives

Develop asset management strategies aligned with objectives of the 7-year Strategic Plan and asset management reporting linking asset performance to strategic outcomes.

Asset Inventory	Asset Condition	Investment Prioritization	Asset Categorization
• Identifies and lists assets (vehicles, facilities, stations, equipment and systems) that are critical for the delivery of services • Specific attributes such as asset class, asset type, purchase date, useful life and replacement costs. • Improved through validation and identification of lead times for renewal.	• Documents knowledge about assets, their condition and performance in a language that everyone can understand.	• The inventory and condition data supports decision-making quality and helps to articulate and justify asset needs.	• Defines the asset hierarchy and criticality at the asset level across the Enterprise • Based on TransLink's ability to deliver customer service. • Initial criticality is assessed on safety, reliability (including risk and emergency planning), and efficiency.

In addition to the information presented in Figure 12, the following is of relevance about the strategy:

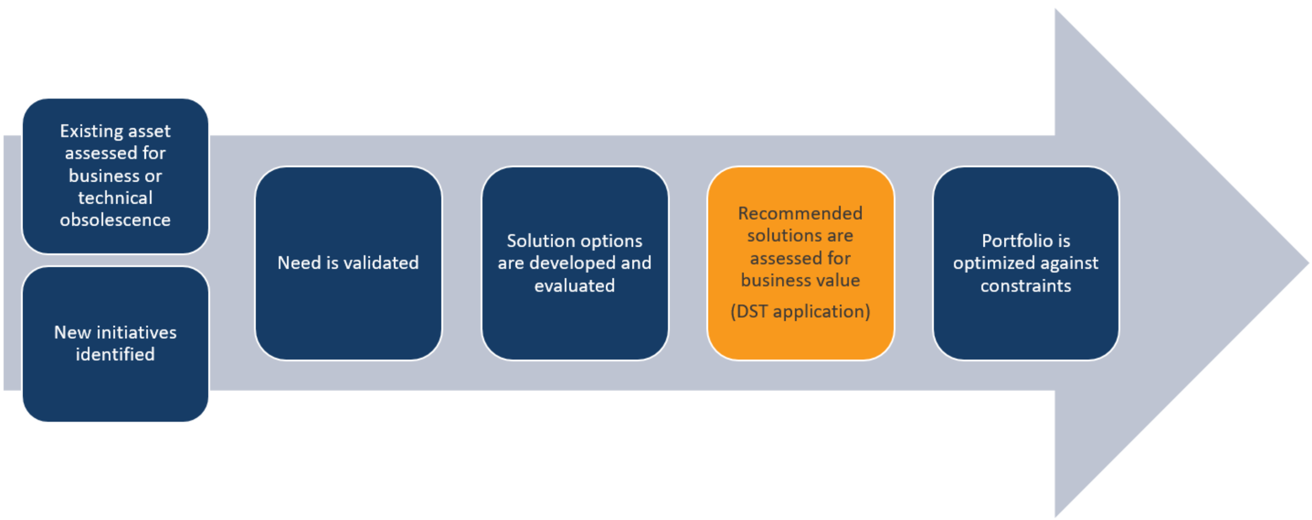
- *Asset inventory* – The asset inventory includes asset attributes and condition information. Between 2019 and 2025, TransLink will continue to enhance this system by continuing to identify and list current assets that are classified as critical for the delivery of services (e.g. vehicles, facilities, stations, roads and bridges). Key attributes associated with these assets are operating group, asset class, asset type, purchase date, useful life and replacement cost.
- *Asset condition* – This is another important aspect of the asset management system. TransLink will continue to populate this information by documenting available information about their assets and their condition and performance. The asset condition of key asset classes is captured within Asset Renewal Programs (ARPg), which are long-term, forward-looking capital programs that justify the asset reinvestment required to maintain a state of good repair based on the entire life cycle of the asset. This approach helps to ensure that the asset management objectives of performance, cost, risk and customer experience are met. This information is expected to be provided and validated by the various agencies that are responsible for each asset.
- *Investment prioritization* – This is a critical component of the system, as this is where the investment prioritization analysis takes place based on the asset inventory and condition data. A Decision Support Tool (DST) has been developed, which serves as a framework that provides a transparent and data-driven way of identifying how TransLink determines the business value for the capital planning approval process. It is intended to be used as part of a broader asset management process where needs are identified, options are developed, preferred options are assessed for overall business value and optimization and prioritization are completed, taking

[12] TransLink Corporate Asset Management Strategy – CAPITAL-M. Special presentation by TransLink staff.

into consideration constraints such as budget, resources, operational impacts, project interdependencies and others. Figure 13 shows the overall process within which the DST is applied.

The current parameters used to evaluate the business value within the DST are: strategy and policy, customer experiences, stakeholder and reputation, business effectiveness, human resources, added safety and security and added environmental benefits[13]. For example, the strategy and policy parameter would measure performance in terms of the value a proposed investment would bring with respect to accomplishing TransLink's corporate objectives. Examples of considerations may include: the criticality of the asset, the level of decay the asset currently shows relative to its life cycle and options to maintain service levels if maintenance is deferred. Other parameters explore different considerations such as number of incidents that occur annually involving a given asset, the probability of safety improvement, explicit inclusion of a request in the 10-year investment plan, the level by which strategic objectives are advanced and others. The relative weights of all parameters are assessed annually to ensure the corporate objectives are met.

Figure 13: Asset management process for state of good repair



Lessons learned

The following lessons have been learned in the design, development and implementation of the DST Framework:

- The success of this strategic framework has been possible due to strong leadership from executive and senior management. There has been enterprise-level support and buy-in, corporate goals and strong sponsorship at all levels.
- Change management has been important. It has been data-driven and proven by peers. The implementation of a proof of concept allowed for feedback throughout the process for continuous improvement.

[13] TransLink's Capital Investment Decision Support Journey – Special presentation by V. Kwan.

- A key aspect of this process has been the ability to demonstrate the value of good asset management practices.
- Stakeholder engagement was essential. Intensive collaboration at all stages of the process resulted in trusted relationships and partnerships that allowed for successful results.
- Having a good public relations strategy was also beneficial, particularly when engaging stakeholders.

A.3.2.3 Saskatchewan highways

This case study addresses pavement preservation practices for roadways with high traffic volumes in Saskatchewan. The case study discusses Saskatchewan's pavement preservation toolbox, which provides guidance on selecting good candidate roadways and preservation treatments.

Overview

Saskatchewan's road network is the largest in Canada on a per-capita basis. The network consists of 26,211 km of highways, including 11,593 km of asphalt concrete pavement, 3,909 km of granular pavement, 4,700 km of thin membrane surface (TMS) highways, 5,730 km of gravel highways and 279 km of ice roads.

The Saskatchewan Ministry of Highways operates an asset management program for pavements, bridges, culverts, geotechnical assets, equipment storage buildings, ferries and airports. The Asset Management Group works under the Operation Standards Division and each engineer operates an independent asset management program that generates and prioritizes projects within a set budget they are assigned. The pavement asset management program has been in place since the late 1990s, with significant data availability and excellent data quality. For a long time, the Province used Vemax software for their pavement management program; however, they are in the process of transitioning to Deighton dTIMS software which is expected to have more advanced analysis capabilities.

In recent years, as a result of restructuring and turnover, the Province deemed it necessary to document all processes involved in pavement preservation practices to ensure new and existing staff would have all the necessary information about the pavement preservation process and what takes place throughout the year to make it happen. As a result, they created a treatment selection toolbox that contains information about the following: business process, treatment selection and treatment types and their definitions. This toolbox is the focus of this case study.

Pavement preservation treatment selection toolbox

Figure 14 shows the elements that comprise the pavement preservation treatment toolbox.

Business process. There are three business processes that describe the steps involved in the annual cycle, responsibilities and timing of each element of the process:

- AM1000 – Strategy Development for Road Networks
- AM2000 – Developing Rolling Treatment Program
- AM3000 – Annual Maintenance Planning

Figure 14: Pavement preservation treatment toolbox

The annual maintenance planning cycle business process has the following objectives[14]:

- Ensure the Province consistently develops an annual work plan for maintenance
- Ensure the plan estimates the amount of work required each year to achieve the provincial standard for each major activity
- Ensure good work methods are identified and adopted
- Maximize the delivered overall level of service for a given investment by evaluating trade-offs between competing interests
- Minimize life-cycle costs by considering the interaction of capital and maintenance costs for deteriorating assets

The timeline for the annual maintenance planning cycle business process is shown in Figure 15.

Treatment selection guide. The Treatment Selection Guide is a detailed document that contains information that assists practitioners in the selection of different types of treatments for pavement preservation. The guide contains a selection of infosheets that provide a snapshot about each treatment, including information such as approximate cost of the treatment, expected life, implementation guidance, how long it has been used in the province and reference to further reading for additional information about the particular treatment.

Definitions of treatment types. The generation of a list of definitions for treatment types is an essential aspect of the toolbox given that there were inconsistencies regarding terminology used to refer to different assets, treatment types and other aspects of the asset management program. Furthermore, because of the frequent turnover, new staff sometimes are not fully knowledgeable about key

[14] Saskatchewan MHI Business Process AM3000 – Annual Maintenance Planning Cycle.

terminology for the program. By creating this list, the agency is now able to standardize terminology to ensure quality.

Treatment grid. The treatment grid allows practitioners to identify a suitable treatment quickly, systematically and consistently for a given location by considering all the decision criteria and all the possible treatment alternatives and to rule out potentially unsuitable treatments. The types of treatments included in the grid are the following: graded aggregate seals, chip seals, microsurfacing, thin lift overlay, repaving, hot in place and cold in place.

This grid distinguishes between information that can be readily accessible at the office (e.g. information from the preservation database or other available databases) and information that must be obtained through a site visit (e.g. specific damage, surface drainage issues). The grid also provides information regarding the types of tests that may be needed for the particular situation being analyzed (e.g. surface friction, deflection).

The advantage of having this treatment grid and the treatment selection guide is that the decision about the type of treatment to select for a given problem has been standardized and it no longer depends on the person doing the work.

Figure 15: Annual maintenance planning cycle business process

Lessons learned

These business processes have been used since 2014, with the following benefits and gaps being identified.

Benefits

- The treatment selection guide is very beneficial for new and inexperienced staff. It acts as a user guide and allows them to make decisions with minimal instruction.
- Having documented processes in place during a reorganization is very beneficial. It allows the transition to occur more smoothly as different facets of the organization are shuffled. (The Ministry's organizational structure was changed in 2018, shifting from regionally managed asset management programs to one provincial asset management group).

Gaps

- Training on the new processes was provided in 2014 but has since been lacking. The Ministry believes that training should occur on a regular basis so newcomers to the Ministry or those taking on different roles know where to find information and can easily understand how and why things are done, what the different treatment types are and the overall asset management process.
- The distribution of process materials has also been lacking since 2014. Although the documents are posted for everyone to review, it is not always made known where to find all the process documents. The Ministry believes that a regular update of all processes should be provided to all staff, particularly when changes are made, so everyone is familiar with where to find the documents.
- A common language dictionary has proven to be necessary. Every district and/or crew has a different naming convention for maintenance activities or material types, which can cause confusion when projects are being implemented. The Ministry believes it is beneficial to have a common language provincially for treatments and maintenance activities, including colloquial names.

A.3.3 State of practice in the United States

Hawkins & Smadi (2013) synthesized transportation asset management (TAM) practice among state highway agencies to provide a resource as a basis for comparison and directing future efforts. The synthesis is based on two surveys, with additional input from practitioners. Several conclusions and recommendations from this synthesis follow:

- It is a considerable challenge to change a transportation agency's culture to initiate, embrace and integrate TAM principles. However, the level of interest among state departments of transportation (DOTs) and other agencies has been steadily increasing.
- About 60%B of agencies have an asset management group. Having executive involvement and an asset management structure is helpful to support implementation and practice.
- Over 70% of responding agencies collect information about signs, guardrails and lighting assets.
- Over 70% of responding agencies noted that since they have started using asset management principles, their decisions are more data-driven, defensible and performance-based.

- The primary performance measures that drive agency decision making are physical condition and safety. Operations and capacity are also common measures, while the concept of risk is a less common measure.
- Risk assessments are activities that require more focus on short-term and long-term planning.

Maggiore & Ford (2015) conducted a practice review to determine the level of sophistication of various state DOTs for making resource allocation decisions. Key findings from the practice review follow:

- For many states, the amount of funding that goes towards addressing a given goal or objective is largely determined by the existing program structure and historical program funding allocations.
- Several states have allocation processes strongly focused on preservation investments, leaving little room for other purposes. Remaining allocations are typically a reflection of desired projects rather than goal-level priorities.
- Some states use "soft-optimization" approaches, whereby decisions are mostly or partly driven by professional discretion and non-technical inputs.
- States coming closest to performance-based cross-asset resource allocation have heavily integrated performance measurement into decision-making approaches. These states use more data-driven approaches, but still require leadership to make professional judgements.

Vandervalk (2018) synthesized information regarding how U.S. DOTs and metropolitan planning organizations (MPOs) manage data, utilize tools and technology, monitor system performance and coordinate with partners. Results from a four-part survey of 41 DOTs and 16 MPOs revealed several findings:

- Most agencies have the data necessary to report on bridge condition measures, pavement condition measures, vehicle-miles travelled (VMT) and safety performance. Many agencies, however, do not have data to identify vehicle occupancy or air quality measures.
- Most states use specialized tools in bridge and pavement performance areas. Approximately half of all agencies surveyed utilize tools in the mobility and safety area. The highest area of need for tool development is pavements.
- Most states develop target-setting measures for safety, while approximately half of all agencies surveyed develop target-setting measures for bridges and pavement. Target-setting measures for mobility are less common.
- DOTs need improved proficiency in staff, consultants and tool capability for all performance areas, with mobility having the highest need.
- Future research is needed to better understand and model the deterioration of pavements and bridges.
- Additional guidance is needed on standardized mobility performance measures and methods of forecasting crashes and the effects of countermeasures.

A.4 Lessons learned

This chapter presents a series of lessons learned from the study that support the implementation of performance-based decision making within asset management programs. The lessons learned are grouped based on the content discussed in each applicable chapter of the report.

A.4.1 Fundamentals of performance-based decision making

This study reveals the following lessons regarding the fundamentals of performance-based decision making:

- Performance management is "the practice of setting goals and objectives; an on-going process of selecting measures, setting targets and using measures in decision making to achieve desired performance outcomes; and reporting results" (Grant et al., 2013). Transportation agencies in North America have increasingly applied performance management to improve program and project delivery with respect to desired performance outcomes, to support decision making as it pertains to funding allocation and investments, to provide transparency and accountability to the public and to comply with good governance practices.
- The implementation of the performance management approach starts with the elements of high-level strategic direction and planning analysis. These elements contribute to programming decisions, which interact with implementation and evaluation activities. The outcomes of ongoing monitoring and evaluation feedback into refined strategies and plans, creating a management cycle that guides decision making over time. Quantitative and qualitative data, including data collected from stakeholder and public consultations, fundamentally underpin all elements of the performance management approach.
- Performance measures may be classified as inputs, outputs and outcomes. *Input measures* reflect the resources available within an agency to carry out a task. *Output measures* reflect the way resources are used, the scale or scope of activities performed and the efficiency of converting allocated resources into a product. *Outcome measures* reflect the degree of success of the agency in achieving its goals and objectives. In practice, input and output performance measures are commonly used, principally because they tend to be easier to monitor and communicate, less expensive to measure, provide more timely indications of performance (compared to long-term outcomes) and offer a basis for relating accomplishment to agency resources needed. While the literature emphasizes the need for increased utilization of outcome measures, agencies suggest that a blend of output and outcome measures should be considered.
- While the number of performance measures should be few, they should cover the spectrum of an agency's objectives. When selecting performance measures, consideration should be given to the following requirements: measurability, forecastability, clarity, usefulness, relevance, multimodality, temporal effects and geographic scale.
- Transportation performance may be measured in numerous ways. At a high level, common categories for measuring transportation performance include: safety, system preservation, system operations, quality or level of service, reliability, connectivity, accessibility, freight

mobility, economic vitality, environmental sustainability, energy security, livability, resilience and organizational excellence.

- The setting of targets is intertwined with the establishment (and refinement) of performance measures that meaningfully direct an agency's activities towards its objectives and goals. While targets can provide a powerful internal motivation for an agency and can help agencies communicate funding needs, equity considerations and uncertainties related to data and technical tools generate some reluctance to apply targets within performance-based decision making.
- Benchmarking involves using compatible measures and data to compare performance outcomes and business practices among organizations doing similar work, with the aim of continuously improving quality and performance. Benchmarking may be conducted independently by an agency or through benchmarking networks comprising peer organizations.
- The literature consistently cites the benefits of implementing performance-based decision making for transportation agencies and the stakeholders they serve. However, despite these benefits, challenges have emerged as performance management approaches have matured, particularly as they become more sophisticated in their use of data and tools, more comprehensive in their application across modes and asset classes and more capable of addressing competing objectives within an agency.
- In Canadian jurisdictions, system preservation (i.e. asset management) has been found to be the most developed and mature application of performance measures. Safety performance is considered a priority interest while sustainability and environmental quality are typically assessed to a limited extent.

A.4.2 Asset management and performance-based decision making

This study reveals the following lessons regarding asset management and performance-based decision making:

- The application of performance-based decision making for asset management has become common practice for transportation agencies. Transportation asset management is a broad concept, which can be defined as "a strategic and systematic process of operating, maintaining and improving physical assets, with a focus on engineering and economic analysis based on quality information, to identify a structured sequence of maintenance, preservation, repair, rehabilitation and replacement actions that will achieve and sustain a desired state of good repair over the life cycle of the assets at minimum practicable cost" (23 U.S.C. 101(a)(2), MAP-21 1103).
- The underlying goal of asset management is to provide greater value to the system and a good level of service for end-users through improvements in program effectiveness and system performance. This requires: a comprehensive asset inventory; up-to-date condition measurement; analytical tools to forecast changes in condition, service, or performance over time; treatment guidelines; and models to estimate treatment costs, implications and effectiveness.
- Performance measures for asset management typically pertain to the preservation of assets, mobility and accessibility, operations and maintenance and safety. Among these areas, the development and application of performance measures for physical assets (pavements and

bridges) are the most mature. Performance measures for other goal areas (e.g. mobility, accessibility, safety) tend to be less advanced.

- Leadership, administrative and institutional issues are commonly cited as barriers to implementing a performance-based asset management program. These barriers arise because of the functional segregation of many agencies, a lack of consistent senior leadership, unpredictable funding, competing objectives within the organization, political influences and external mandates for establishing benchmarks and reporting performance. Engaged leadership, an agency-wide commitment to knowledge management and the adoption of technically sound and data-driven practices help address these challenges.
- One of the most important aspects of a transportation asset management program is meeting the needs of people within an organization. This can be supported by ensuring that senior management buys into the process and having visible and active champions to guide and support the successful implementation and operation of the program.
- Life-cycle costs are the series of costs incurred over the asset's life cycle (planning, construction, maintenance, renewal and disposal). Practices are well established for using life-cycle cost analysis to compare different design alternatives for pavements and bridges. However, these practices are typically intended for applications at the project level, after a substantial amount of detail has been established. Practicing effective asset management across asset classes requires a broader consideration of programmatic life-cycle costs and the application of life-cycle cost concepts to establish short- and long-term budget levels and predict future performance and funding needs.
- As transportation agencies embrace the need for sustainable systems, asset management practices need to align with broad economic, social and environmental objectives. Evidence of this shift has emerged within the management of a single asset class (e.g. pavements, bridges) and has, in part, compelled agencies to consider cross-asset resource allocation. More broadly, there is a recognition that sustainability, as it relates to asset management involves proactive consideration of current and future user demands for highway infrastructure and responsible adoption of demand-responsive policies and technologies.
- Appropriate budgeting and allocation of funds for operations and capital investments is a challenge within asset management, but one that performance-based approaches can help address. Robust asset management, coupled with meaningful financial reporting is essential for efficiently and effectively maintaining infrastructure systems. However, despite the important link between performance-based asset management and financial decision making, not all agencies successfully link these administrative processes.
- As asset management programs mature, issues involving priority setting between program elements have emerged. Such issues can span across modes and/or asset classes. Linking system performance with project programming requires consistent definition and application of outcome measures. In addition, agencies may use optimization techniques that emphasize projects that maximize the performance of a full program, subject to constraints. Successful implementation requires tracking performance and comparison with expected targets.
- Effective implementation of performance-based decision making relies on the availability of reliable data. Among the key challenges associated with performance-based asset management identified, many relate to the cost-effective production and maintenance of consistent, timely and quality data. The development of agency-wide data governance strategies, the appointment

of data stewards and the implementation of flexible data warehousing systems help address these challenges.

A.4.3 Optimization methods in asset management

Agencies use a variety of tools for performance-based decision making. These tools can increase the effectiveness and transparency of analyses involving optimization, evaluation, prioritization and resource allocation. The type of method used is largely dependent on the of level technical knowledge, agency's historical preference, robustness of the asset management program and others. This study reveals the following lessons:

- The allocation of limited resources within an agency requires technical tools and sound judgement by a range of decision makers. While many potential methods and techniques are available for optimization of resource allocation, existing tools are not well suited for guiding practical decision-making processes which cross the boundaries of asset type (e.g. pavement versus bridge), mode (e.g. highway versus transit), work class (e.g. maintenance, operations, construction), or objective (e.g. safety, preservation, mobility).
- Engineering economics tools assist resource allocation decisions by monetizing various agency, user and societal costs and benefits over the life cycle of an asset. These tools enable comparison and evaluation of alternative courses of action by converting various costs and benefits into monetary units and accounting for the time value of money through the use of a discount rate, even if alternatives are expected to have different service lives. The application of engineering economics principles to asset management has become common practice, despite limitations concerning discount rate uncertainties, monetization of certain types of costs and benefits, an inability to account for multiple stakeholder viewpoints, potential misalignment of economic analysis results with agency goals and the need to integrate risk-based and probabilistic techniques. Consequently, the literature refers to these as near-optimization tools.
- Risk assessment and risk management techniques have been increasingly integrated into asset management practices. Risk assessment refers to the scientific process of measuring risks in a quantitative and empirical manner. It typically occurs before risk management, which is a qualitative process that involves judging the acceptability of risks and implementing measures to reduce them to acceptable levels. While beneficial for asset management programs, the assessment and management of risks requires a significant level of effort and expertise, potentially disregards qualitative inputs in an increasingly quantitative exercise and necessitates careful protocols for communicating risks to decision makers and other stakeholders.
- One of the core principles of asset management is the analysis of options and trade-offs. This involves considering how different resource allocation decisions affect the achievement of policy objectives and the limitations posed by realistic funding constraints given the range of relevant options and trade-offs. The goal is to formulate and optimize a representative set of multi-objective mathematical functions for relevant performance measures.
- The concepts of Pareto solutions and criteria weighting underpin multi-objective or trade-off analyses. A Pareto solution identifies the set of alternatives that cannot be improved with respect to one criterion without degrading performance for other criteria. Pareto solutions are helpful when there are no agreed upon relative weights for the criteria. If criteria are weighted, alternatives can be scored and ranked accordingly. Weights are usually calibrated to reflect

stakeholder preference. So, in essence, the decision maker has to select a satisfactory solution from a set of Pareto optimal solutions based on some specific judgment and value system.

- The literature identifies numerous multi-objective optimization methods applicable to transportation asset management, including weighted sum method, goal programming method, multiplicative utility function method, compromising programming method, Ɛ-constraint method, multi-attribute utility theory, analytic hierarchy process and various types of genetic algorithms.
- Multi-objective optimization or decision analysis methods can be conducted using a top-down or bottom-up approach. In a top-down approach, program level trade-off analysis is conducted to identify funding levels based on how each asset or program will respond to a given funding level. The responses (i.e. performance) are used to create response curves, showing performance measures as a function of the funding level. Projects are then prioritized based on the level of funding available for that asset and the ability to satisfy the goals identified for that asset or program. In a bottom-up approach, a set of projects are selected from potential projects spanning all assets, which maximize the overall measure of performance (i.e. utility). The trade-off analysis is conducted at the project level. Unlike the top-down approach, there are no direct results showing the implications of the level of funding applied to an asset class. This can raise technical challenges associated with developing robust and universal algorithms and the collection of good quality data.
- Cross-asset resource allocation is the process of determining how to allocate funding across multiple types of assets (e.g. pavements, bridges, appurtenances) or investments. Despite technical advances, most current transportation asset management practices address resource allocation within a single asset class, but the potential for a more holistic approach has motivated agencies to seek structured cross-asset optimization approaches. The Delphi method (a qualitative, expert-driven decision-making approach) and various multi-objective optimization methods have been successfully implemented.

A.4.4 Implementation of performance-based decision making for asset management

Until now, relatively little recent information is available on this subject in the Canadian context. The survey conducted as part of this project, coupled with the three case studies reveal the following lessons:

- Pavements are the most common asset class for which most Canadian agencies have asset management programs in place, followed by bridges.
- When considering all types of asset management programs, agencies are generally highly satisfied with their asset management programs as it pertains to data quantity, data quality, data completeness and data currency. Further, because pavement asset management programs have been in place longer than other types of programs, these programs show the highest satisfaction level with data quantity.
- Asset management programs for paths and sidewalks, show the lowest level of satisfaction by Canadian agencies, mainly due to software capabilities, currency and staff turnover.
- Intangible assets such as data and human capital are, for the most part, not included as part of agencies' asset management programs in Canada. However, for those agencies that do operate

asset management programs for intangible assets, data was reported as being the most common intangible asset.

- Most Canadian agencies do not apply cross-asset optimization. For those that do, the most common combination of asset classes in cross-asset programs are:
  - Pavements and bridges
  - Pavements and subsurface infrastructure
  - Bridges and culverts
  - Pavements and culverts
  - Pavements and paths and sidewalks
- A series of common challenges have been identified by Canadian agencies with respect to resource allocation to transportation infrastructure asset management. The most common are:
  - Limited available staff time and contractor resources to develop, operate and maintain a program as well as limited budget and resources for required staffing
  - Ensuring a robust and consistent understanding of all asset needs for maintenance, growth and expansion (i.e. creating an inventory of assets and assessment of conditions)
  - Consistency and timely program delivery due to inadequate funding and staffing; delays in implementing preservation treatments for the right asset at the right time lead to accelerated deterioration that result in costlier treatments
  - Complexity of technology and the need for expertise other than civil engineering
  - Extreme weather and geotechnical (permafrost) condition
  - A well-established cross-asset allocation method that optimizes investments across various asset classes in the whole transportation system
  - Lack of best practice asset management for other assets besides pavements and structures (e.g. rest areas, truck inspection stations, ferry services, remote airports, illumination, guardrails, median barriers, traffic signals, signs, salt domes, patrol yards)
  - Moving towards a more service-oriented asset management approach versus the older traditional asset-centric model that includes a multimodal and active/mass transportation perspective
  - Institutional challenges such as the procurement process for software programs and changing plans for infrastructure investments
  - Political pressures for other capital infrastructure
  - Lack of leadership and understanding from senior decision makers regarding the value of an asset management program

The three case studies conducted as part of this project revealed the following findings:

- Designing, developing and implementing a performance-based asset management program takes vision and good leadership, collaboration and commitment, which were also identified in the literature as key success elements.
- Data-driven change management is important. The implementation of a proof of concept can allow for feedback throughout the process for continuous improvement. A data-driven approach can also help to demonstrate the value of good asset management practices.
- Investing in data collection and maintenance will greatly assist in supporting data-driven decisions. High-quality data is perceived as being the most important asset in a robust asset

management program since infrastructure investment cannot happen without access to good quality data. To ensure an agency can successfully make the argument for the importance of data, evaluate the replacement value of the data owned and what the implications would be on the overall asset management process in the absence of that data.

- Important parameters that can be used to evaluate the business value within an asset management decision support system are: strategy and policy, customer experiences, stakeholder and reputation, business effectiveness, human resources, added safety and security and added environmental benefits.
- The relative weights of all parameters used in decision making should be assessed annually to ensure corporate objectives are met.
- Stakeholder engagement is essential to ensure collaboration at all stages of the process. This results in increased trust and partnerships that ensure success.
- A strong public relations strategy is beneficial, particularly when engaging stakeholders.
- Special asset management training for staff can help with the success of a program, by ensuring that staff skills are up to date with best practices.
- Documentation of all processes that comprise the asset management program is essential, particularly if the agency undergoes a reorganization. This documentation allows for a more successful and seamless transition to occur, with minimal interruptions to the asset management program.

Part B:
Practitioner toolkit

Overview

As evident in the literature and the review of current practices presented in Chapter A.3, agencies use a variety of tools for performance-based decision making. These tools can increase the effectiveness and transparency of analyses involving optimization, evaluation, prioritization and resource allocation. For example, the jurisdictional survey found that GIS is the most commonly used tool by agencies across the country for asset management, with 58% of respondents indicating that they use GIS extensively, while off-the-shelf asset management software programs were the least common with 32% of respondents using them. Some of the commonly specified tools (either off-the shelf or tailored tools) used by the responding jurisdictions to conduct optimization of asset resource allocation are: Stantec's Highway Pavement Management Application (HPMA) and Bridge Management (BMS) systems, Vemax Suites, dTIMS, MS Access, MS Excel, Geomedia and ArcGIS programs.

Survey participants also provided insight regarding the types of tools that would be most beneficial to their agency for performance-based decision making. Tools for data management would be most beneficial and tools for specifying software requirements were identified as the least beneficial type by respondents.

From the telephone interviews conducted with agencies across the country, the following types of tools were identified as beneficial:

- Tools to evaluate investment levels
- Tools to identify needs and solutions
- Tools to compare options
- Tools to monitor results
- Tools to manage data
- Tools for cross-asset optimization
- Tools for software requirements
- Tools to compare asset conditions across municipalities and provinces
- Tools to track historical data and projected results on asset performance vis-à-vis actual conditions
- Tools for visualization

The literature review revealed additional tools that could be beneficial for a performance-based asset management system, including:

- Tools to value data
- Tools for time-series analysis/trends
- Tools for interacting with public officials and the general public
- Tools to display the value of preventive maintenance
- Tools to translate manual data collection to automated data collection methods

Based on this information, the project team developed the toolkit contained in this chapter to assist practitioners in the selection of tools that can assist with performance-based decision making. The tools contained in this toolkit are based on readily available information; they are practical, transparent, outcome-driven and based on sound technical knowledge. These tools can help guide practitioners at higher levels of decision making.

As shown in Figure 16, the toolkit contains tools within three broad categories: data management; analysis and evaluation; and communication. These categories were developed based on the input gathered from surveys, interviews and the literature.

This toolkit contains five tools for data management:

- Data governance
- Quality assurance
- Data collection planning
- Data warehousing, storage and access
- GIS tools

It also contains seven tools for analysis and evaluation:

- Life-cycle cost analysis
- Present worth
- Internal rate of return
- Benefit/cost
- Risk assessment and risk management
- Cross-asset optimization
- Multi-objective optimization

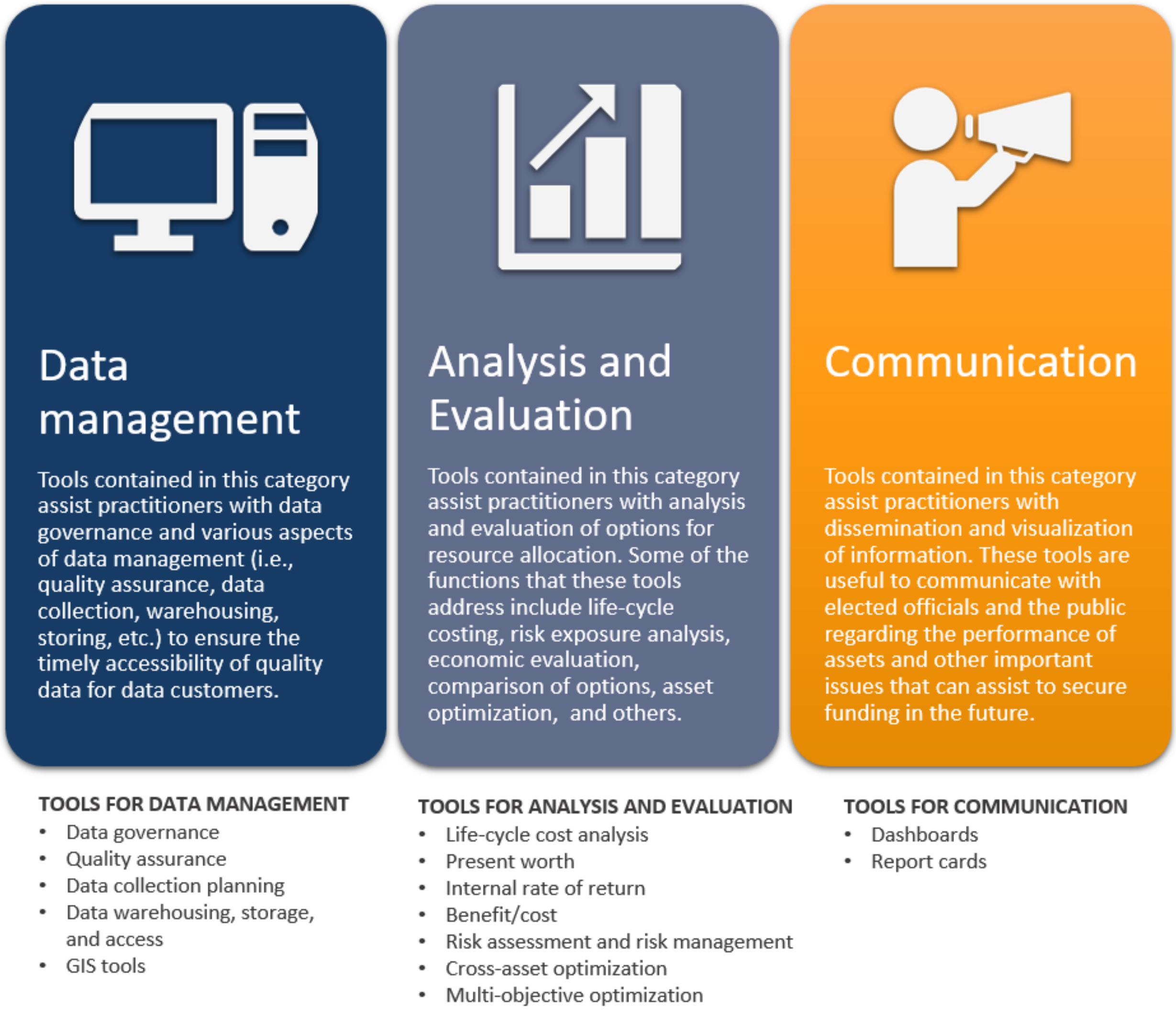
Finally, it contains two communication and visualization tools:

- Dashboards
- Report cards

The following information sheets present detailed characteristics of each tool:

- *Effectiveness* – Based on literature and practice, how effective is the tool expected to be once implemented or applied (low, medium, high, unable to assess)?
- *Required level of commitment* – What level of institutional commitment is required to implement the tool (low, medium, high, unable to assess)?
- *Data needs (for the Analysis and Evaluation Tools and the Communication Tools)* – How comprehensive is the data required to implement the tool (low, medium, high, unable to assess)?
- *Required level of expertise* – What level of technical expertise is required to implement the tool (low, medium, high, unable to assess)?
- *Effort for implementation* – How much institutional effort (resources) will be required to implement the tool (low, medium, high, unable to assess)?
- *Overall performance* – Overall, how well is the tool expected to perform once implemented (low, medium, high, unable to assess)?

Figure 16: Practitioner toolkit framework



B.1 Data management tools

B.1.1 Data governance

Overview

The term "data governance" is often used interchangeably with the term "data management," however it is useful to distinguish these concepts. Unlike data management, which involves a wide range of data-driven activities directed at achieving established goals and objectives, data governance ensures that the data itself is properly managed so that it can support these data-driven activities. Specifically, the NCHRP defines data governance as "the establishment, execution and enforcement of authority over the management of data assets."

Considering data as an asset compels agencies to extend the performance-based asset management practices normally applied to physical assets to data assets. For example, the experiences of the Regional Municipality of York (see Section A.3.2.1) offer an instructive case study on how agencies might transition to considering data as an asset.

Key practices that should be considered follow:

- Resource allocation decisions must be based on a well-defined set of policy goals and objectives.
- Data asset management must be performance-based, where policy objectives are translated into system performance measures that can be applied on a day-to-day basis or for strategic management.
- Funding allocation (i.e. investments in data management) must be based on evidence resulting from an analysis of how different funding allocations will impact the achievement of policy objectives.
- All decisions must be based on credible, current and good quality data (in this case, data about data), which can be mined to assess the current condition (or quality) of each data asset and is accessible within a structured data architecture.
- Performance results (i.e. how well the data achieved stated policy goals and objectives) must be monitored for impacts and effectiveness and must be communicated regularly.

Characteristics

Effectiveness

Low	Med	High	Unable to assess
☐	☐	☐	☑

Required level of commitment

Low	Med	High	Unable to assess
☐	☐	☑	☐

Required level of expertise

Low	Med	High	Unable to assess
☐	☑	☐	☐

Effort for implementation

Low	Med	High	Unable to assess
☐	☐	☑	☐

Overall performance

Low	Med	High	Unable to assess
☐	☐	☐	☑

Key sources

- Gharaibeh et al. (2017)
- Stickel and Vandervalk (2014)
- Ladley (2012)
- Cambridge Systematics (2010)
- Cambridge Systematics (2006)
- Neumann and Markow (2002)
- AASHTO Core Data Principles (https://data.transportation.org/aashto-core-data-principles/)

To support the implementation of these practices, this *Data Governance Tool* comprises three components designed to help agencies establish: (1) core data principles; (2) a data governance structure; and (3) data domains and sub-domains. Since formal data governance practices have yet to be widely implemented, there is a need for transportation agencies to evaluate and quantify their long-term costs and benefits.

Core data principles

The establishment of core data principles underpins the implementation of data governance practices. The seven core data principles shown in Table 13 are designed to raise the profile and importance of data within the context of transportation agencies. Given the important role that data plays in performance-based decision making—whether applied to physical asset management or other agency functions—these principles provide a foundation for all data management tools.

Table 13: Core data principles

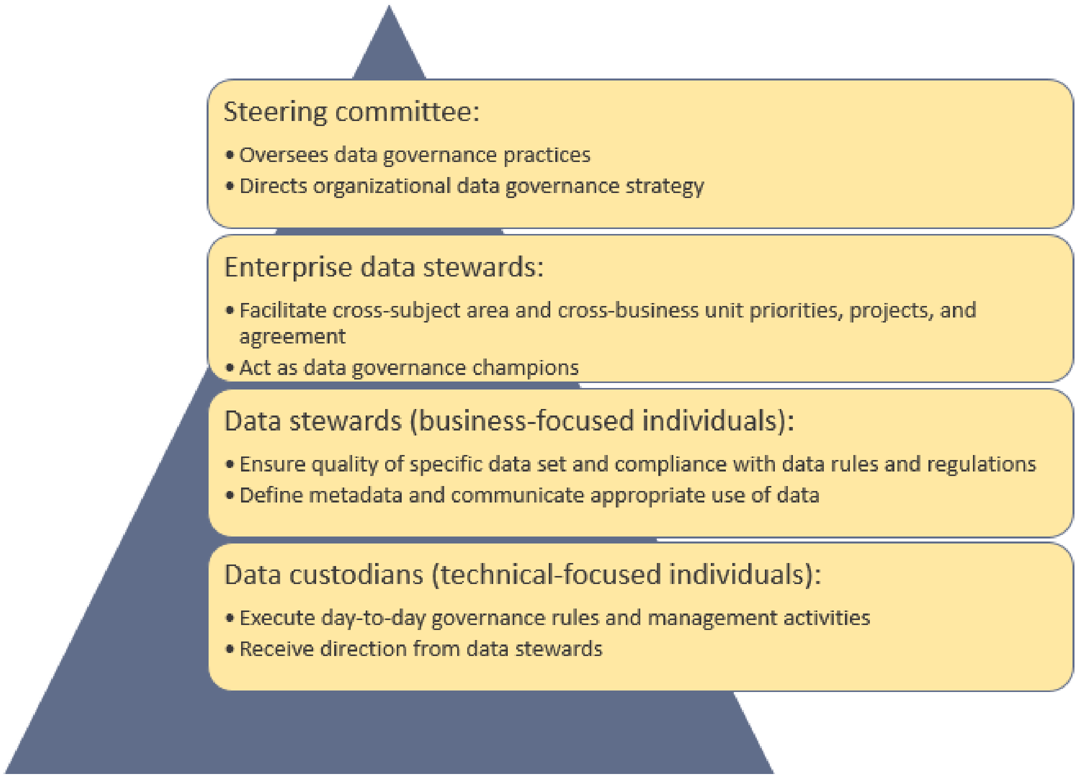
Principle	Description
Valuable	Data are an asset - Data are a core business asset that has value and are managed accordingly.
Available	Data are open, accessible, transparent and shared - Access to data is critical to performing duties and functions, data must be open and usable for diverse applications and open to all (i.e. accessible to those who need it).
Reliable	Data quality and extent is fit for a variety of applications - Data quality is acceptable and meets intended needs.
Authorized	Data are secure and compliant with regulations - Data are trustworthy and safeguarded from unauthorized access, whether malicious, fraudulent, or erroneous.
Clear	There is a common vocabulary and data definition - Data dictionaries are developed and metadata established to maximize consistency and transparency across systems.
Efficient	Data are not duplicated - Data is collected once and used many times for many purposes.
Accountable	Decisions maximize the benefit of data - Timely, relevant, high quality data are essential for decision making.

Data governance structure

A mature data governance structure comprises three key elements: people, processes and technology.

People. Establishing a data governance structure requires careful definition of the roles and responsibilities of the people charged with various aspects of data governance and management. Figure 17 depicts four suggested roles: a data governance steering committee, enterprise-level data stewards, business-focused data stewards and technical focused-data custodians.

Figure 17: Hierarchical data governance structure



Processes. The second key element of a data governance structure is the set of processes required to implement the structure.

- *Strategy development and alignment* – This process involves establishing an organizational data governance strategy and mapping the strategies of each business unit within this broader strategy.
- *Business needs assessment* – This process involves curating and documenting business requirements for various agencies technologies or solutions. For example, a pavement management system would require a business needs assessment to identify the activities and protocols that the agency needs to support its implementation.
- *Data standards establishment and maintenance* – This process involves adding new and maintaining existing data and metadata standards for data held across an agency's functional areas. See the *Generation of Metadata Tool* later in this section for further details.
- *Data-related education, training and guidance* – This process involves equipping various data customers (internal and external) with the knowledge and skills needed to fulfill their data-related tasks and duties.
- *Quality monitoring* – This process involves establishing data quality agreements, assessing data quality (in its multiple dimensions), data screening and validation and ongoing monitoring of data quality. See the *Data Quality Assurance Tool* later in this section for further details.

Technology. The third key element of a data governance structure is the technology that supports the various processes listed above. Technology and tools (including those described in this toolkit) are needed to support tasks such as data management, data fusion, data extraction and transformation, data analysis and predictive modeling, metadata recording and sharing and data reporting.

Transportation data domains and sub-domains

Transportation agencies manage numerous and often disparate data sets. Over time, the need for these data sets changes, meaning that new data is likely to emerge in response to customer needs and certain data needs may no longer be important to the agency's functions. Regardless of the current availability of data within an agency's inventory, an agency should establish and periodically revise data domains and sub-domains needed to support its functional areas. Figure 18 provides an example template, adapted from the Minnesota Department of Transportation's data governance model, to define data domains and potential data sub-domains.

Figure 18: Example template for a transportation agency's data domains and sub-domains

Data domain	Domain description	Data sub-domains
Business stakeholder/customer	Data on the interface with external stakeholders and data about internal and external communications	[number, table reference]
Financial	Data related to receiving, managing, and spending funds	[number, table reference]
Human resources	Data about individual employees	[number, table referen
Infrastructure	Data on the basic facilities that make up or interface with the transportation system	13, Table 13
Planning, programming, and projects	Data that provide direction for and management of projects	[number, table re
Recorded events	Data on time-based occurrences that take place on the transportation system or that affect the transportation system	[number, table re
Regulatory	Data on topics that are controlled or directed by legal requirements	[number, table refer
Spatial	Data that define locations in terms of geographic coordinates (e.g., in a GIS), Cartesian coordinates (e.g., in CAD), within a linear referencing system (LRS), or spatial boundaries	[number, table referen
Supporting assets	Data on items that affect or support the transportation system (e.g., building and facility, fleet, communications)	[number, table reference]

Data sub-domain
Airport
Bicycle
Bridge
Drainage structure
Interchange, intersection, and section
Parking facility
Rail crossing
Right-of-way and contaminated property
Roadway
Safety feature
Sidewalk
Road surface
Traffic control device

B.1.2 Quality assurance[15]

Overview

Quality assurance procedures are an integral part of any data-driven, performance-based program within a transportation agency. While quality assurance and quality control are often considered interchangeably (as in the familiar acronym QA/QC), quality assurance is a broader concept that includes quality control (or data validation) as one of its components. As depicted in Figure 19, quality assurance may include:

- Instilling and adhering to guiding principles
- Establishing data quality measures
- Implementing formal staff training programs
- Establishing rigorous equipment procurement, installation and testing protocols
- Committing to ongoing equipment maintenance practices
- Developing robust data validation (quality control) processes
- Evaluating the program to ensure that it meets its goals with available resources

Jurisdictions should formalize and document their quality assurance rules and procedures. Clear documentation helps automate components of a program, supports staff transitions and succession planning and ensures consistent practice over time and between staff.

Committing to quality assurance requires significant and sustained efforts, leadership from management and executive-level support. High-quality data provides jurisdictions confidence to share information, supports better decision making and investments, minimizes the risk of misusing and misinterpreting data and can facilitate program visibility to attract additional funding for the program.

This tool provides additional details on three components of quality assurance: (1) establishing program-level guiding principles; (2) establishing data quality measures; and (3) program evaluation.

Characteristics

	Low	Med	High	Unable to assess
Effectiveness	☐	☐	☑	☐
Required level of commitment	☐	☑	☐	☐
Required level of Expertise	☐	☑	☐	☐
Effort for implementation	☐	☑	☐	☐
Overall performance	☐	☐	☑	☐

Key sources

- Gharaibeh et al. (2017)
- Regehr et al. (2017)
- Rempel, Regehr and Montufar (2013)
- ASTM (2010)
- FHWA (2004)
- Cambridge Systematics (2000)

[15] Aspects of this tool are excerpted and/or adapted with permission from Regehr et al. (2017).

Figure 19: Components of quality assurance

Program-level guiding principles

Six principles guide the management of information within performance-based transportation programs and provide the foundation for quality assurance within those programs. Table 14 describes these principles.

Table 14: Principles for managing information in performance-based transportation programs

Principle	Objective
Responsiveness to needs	Supply users with required data, in a timely manner and in the format preferred; handle requests for information quickly; provide the most up-to-date information
Truth-in-data	Provide metadata describing the methods and technologies used, the estimated accuracy and reliability of statistics and the data sampling and factoring procedures applied
Consistent practice	Adopt standard methods or encourage standards to be established; conform to standard practice
Base data integrity	Screen raw data for errors and anomalies; the raw data may be accepted or rejected but not adjusted or imputed
Data interoperability	Data should be shared and collection efforts coordinated; the traffic information system must link to other databases
Future flexibility	The system should be flexible and modular to accommodate new technologies and new methods

Sources: Regehr et al. (2017); Rempel, Regehr and Montufar (2013); ASTM (2010)

Data quality measures

Data quality is a critical component of any performance-based transportation program. Data quality is a multi-dimensional concept that considers the *intrinsic* quality of the data, the *context* within which the data is produced and used, the ability of the data to sensibly and concisely *represent* some aspect of what has been measured and the *accessibility* of the data to data customers.

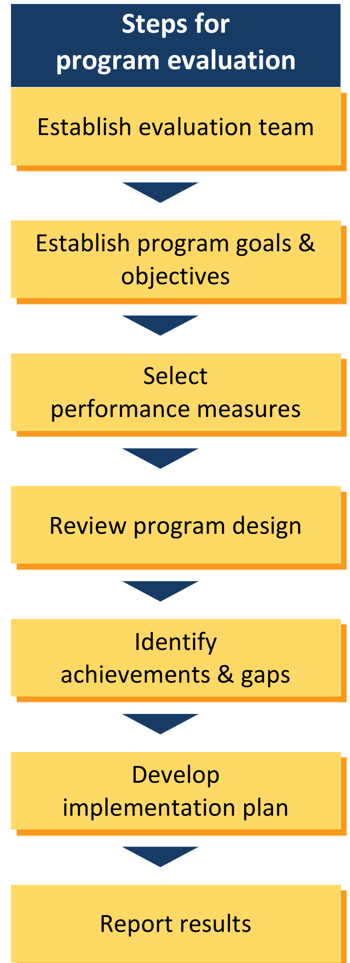
Table 15 shows a quick-assessment checklist to help practitioners consider the quality of their data holistically. A concise list of performance metrics should be chosen to assess each data quality measure. Specific metrics depend on the type of transportation program being considered and may be either quantitative or qualitative. For example, data accuracy might be assessed quantitatively by calculating the mean absolute percent error, whereas data accessibility might be qualitatively assessed in terms of the degree of user-friendliness.

Table 15: Data quality quick-assessment checklist

Assessment [☑ or ☒]	Data quality measure	Category and assessment question	Metric(s) used to assess *[list metrics in this column]*
☐	Accuracy	*Intrinsic*: How well do measured values agree with values assumed to be correct?	*Metric_1 … Metric_n*
☐	Validity	*Intrinsic*: How well do the measured values fall within specified acceptance requirements?	*Metric_1 … Metric_n*
☐	Precision	*Intrinsic*: How reliably do measured values reflect an accepted reference value? Are the measurements repeatable?	*Metric_1 … Metric_n*
☐	Relevancy	*Contextual*: How well do the data meet customer needs?	*Metric_1 … Metric_n*
☐	Completeness	*Contextual*: How much data has been collected compared to the amount of data expected to be collected?	*Metric_1 … Metric_n*
☐	Timeliness	*Contextual*: How much time has elapsed between when data are provided and when they were requested or desired?	*Metric_1 … Metric_n*
☐	Consistency	*Representational*: How similar do the data values remain over time for various processes and applications?	*Metric_1 … Metric_n*
☐	Spatial coverage	*Representational*: How well do the data represent spatial variability?	*Metric_1 … Metric_n*
☐	Temporal coverage	*Representational*: How well do the data represent temporal variability?	*Metric_1 … Metric_n*
☐	Accessibility	*Accessibility*: How easily can data customers access and manipulate data to suit their needs?	*Metric_1 … Metric_n*
☐	Access security	*Accessibility*: How securely can various data customers (internal and external) access the data they need?	*Metric_1 … Metric_n*

Sources: Regehr et al. (2017); Gharaibeh et al. (2017); FHWA (2004)

Existing program evaluation



Evaluation is an essential component of assuring quality within any transportation agency program. Periodic evaluation (e.g. once every five years) ensures that the program meets its goals with available resources. Notably, both program goals and resources may change as new customer needs, data sources and data collection technologies emerge.

Program evaluation should apply a performance-based management approach, which considers program performance in terms of inputs, outputs and outcomes. In general, a performance-based program evaluation should involve the following steps:

1. *Establish the evaluation team* – The team may include the current program manager, functional experts (e.g. data collection experts, data analysts) and data customer representatives.
2. *Establish program goals and objectives* – Program goals are broad statements describing the desired state or function of the program. Objectives are concrete steps toward achieving a goal, stated in measurable terms with or without a specific performance target.
3. *Select measures (or indicators) used in the program evaluation* – These should be selected to enable the monitoring of progress toward objectives and goals. Consider the following:
    - *Measurability* – Agency's capability to consistently generate the measure, data availability, methods used by the agency to produce the measure
    - *Forecastability* – Reliably of the measure for comparison of alternative projects or strategies
    - *Clarity* – Level of understanding of decision makers and stakeholders about the measure
    - *Usefulness* – Relationship of the measure to the issue of concern; ability of the measure to diagnose the problem
    - *Relevance* – Meaningfulness of the measure to track and evaluate progress relative to established objectives
    - *Multimodality* – Applicability of the measure to multiple modes of travel; objectivity and fairness of the measure for decision making across modal silos
    - *Temporal effects* – Temporal meaning of the measure (does it have a consistent meaning over time?); timeliness of the measure to support decisions
    - *Geographic scale* – Applicability of the measure across appropriate geographic scales, including across jurisdictional boundaries
4. *Review program design* – A review of the overall program design provides the information required to develop the performance measures identified for program evaluation.
5. *Identify achievements and gaps* – This step uses the performance measures identified in Step 3 to assess how well the existing program (reviewed in Step 4) meets the program goals and objectives

identified in Step 2. Both achievements (areas where the program meets objectives) and gaps (areas where the program fails to meet objectives) should be documented.

6. *Develop an implementation plan* – This plan formulates strategies and tactics to make necessary improvements to the program. The implementation plan should prioritize areas of improvement and identify whether improvements are expected in the short, medium, or long term.
7. *Report results* – The results of the performance evaluation process should be reported to those involved in the data governance process, program stakeholders and data customers. Consideration should also be given to making the results of the performance evaluation available to the general public.

B.1.3 Data collection planning[16]

Characteristics

Effectiveness

Low	Med	High	Unable to assess
☐	☐	☑	☐

Required level of commitment

Low	Med	High	Unable to assess
☐	☑	☐	☐

Required level of expertise

Low	Med	High	Unable to assess
☐	☑	☐	☐

Effort for implementation

Low	Med	High	Unable to assess
☐	☑	☐	☐

Overall performance

Low	Med	High	Unable to assess
☐	☑	☐	☐

Key sources

- Regehr et al. (2017)

Overview

Effective data collection planning is needed to support performance-based decision making. As shown in Figure 20, this tool provides guidance about four elements of data collection planning, namely: (1) customer data needs survey; (2) data source inventory; (3) data sampling strategies; and (4) data collection improvement priorities.

Figure 20: Elements of a data collection plan

Customer data needs survey

A customer data needs survey can be used to assess and prioritize customer data needs. This survey may be incorporated as part of the overall program evaluation process (see *Existing Program Evaluation Tool*) and its results can supplement engineering judgement concerning data needs. In general, the survey should aim to gather information about:

- Respondent identification and agency
- Data types required
- Specific data elements required
- Data format and reporting requirements
- Data quality expectations
- Temporal and spatial coverage requirements
- Metadata requirements
- Timeliness of data availability and accessibility requirements
- Current applications of the data
- Expected future applications of the data

[16] Aspects of this tool are excerpted and/or adapted with permission from Regehr et al. (2017).

Data source inventory

The data source inventory should align with the data domains and sub-domains identified in the *Data Governance Tools*. When compiling the inventory of data sources, consider data sources that currently or potentially contribute to meeting program objectives. For most agencies, developing the inventory of existing data sources should be relatively straightforward. Compiling an inventory of non-traditional data sources—including those available to neighbouring agencies or those provided by private entities—poses challenges but offers opportunities for data sharing and realizing cost efficiencies as an agency.

Data sampling strategies

Data sampling strategies influence several data quality dimensions (see the *Quality Assurance Tool*) and will be impacted by the level of agency resources available (human, equipment, financial). Agencies should specifically consider the following when developing data sampling strategies:

- Desired intrinsic data quality (i.e. accuracy, precision, validity)
- Desired contextual data quality (i.e. relevancy, completeness, timeliness)
- Desired representational data quality (i.e. consistency, spatial/temporal coverage)
- Applicability of data from external sources (e.g. other departments/agencies, private sector)
- Protocols for failed data collection activities (e.g. data recovery, sampling repetition)

Data collection improvement priorities

The need to define and update data collection improvement priorities arises as customer expectations evolve, new technologies emerge or existing technologies deteriorate, or innovative practices become mainstream. Implementing improvements, however, requires access to resources, which are often insufficient to meet all the needs of a program. Therefore, it is prudent to include and regularly update a list of improvement priorities as part of the Data Collection Plan. The existence of this list ensures that expenditures can be quickly and confidently mobilized should resources become available. Consideration should be given to the following items.

Customer-related considerations

- Need for new or different data types
- Need for more reliable data
- Need for better or real-time access to raw data

Technology-related considerations

- Spatial and temporal coverage
- Equipment performance and reliability
- Equipment calibration and verification requirements
- Comparison of existing data collection practices to known best practices
- Processing requirements for data from new collection equipment

Management considerations

- Capital and operating costs
- Human resource implications
- Timeframe for implementation

B.1.4 Data warehousing, storage and access[17]

Overview

The extent and complexity of the data managed by a transportation agency require effective data warehousing, storage and access control practices. Careful design, development and implementation of these practices help an agency's various programs produce quality, interoperable data products for its customers. This tool comprises the following five components:

- Designing an architecture for data warehouses
- Establishing data retention and storage protocols
- Defining data access control
- Generating metadata
- Evaluating in-house versus commercial off-the-shelf database management tools.

The content of this tool is primarily directed at enterprise-level data stewards, data-stewards for specific business units or functional areas and technical-focused data custodians (see *Data Governance Tool*). It is not intended to provide detailed guidance for information technology (IT) professionals; however, it acknowledges that the growing complexity of transportation data increasingly demands IT (or equivalent) expertise. Moreover, given the rapid advancement of commercially-available database tools, this section avoids referencing specific product brands.

Architecture for data warehouses

Designing the architecture for transportation data warehousing depends on the business structure and requirements of an agency and its programs. Despite the inherent diversity, Figure 21 provides a schematic for a common data warehousing architecture.

Characteristics

Characteristic	Low	Med	High	Unable to assess
Effectiveness	☐	☐	☑	☐
Required level of commitment	☐	☐	☑	☐
Required level of expertise	☐	☐	☑	☐
Effort for implementation	☐	☐	☑	☐
Overall performance	☐	☐	☑	☐

Key sources

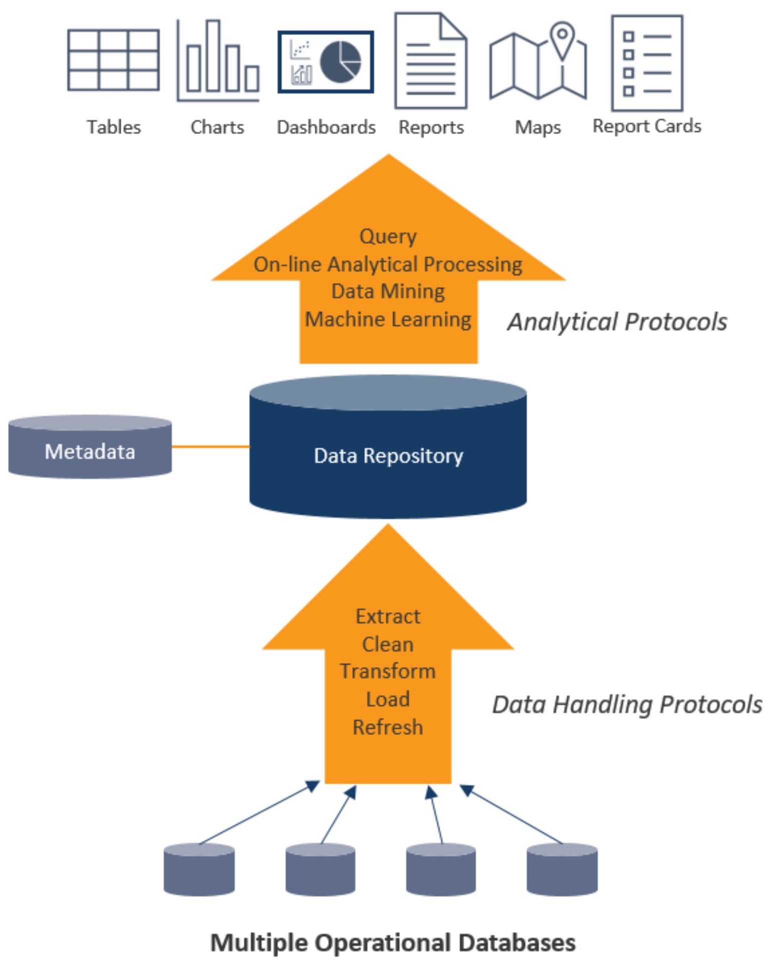
- Regehr et al. (2017)
- Gharaibeh et al. (2017)

[17] Aspects of this tool are excerpted and/or adapted with permission from Regehr et al. (2017).

The architecture comprises the following elements:

- *Operational databases* – These databases support an agency's day-to-day activities (e.g. pavement condition database, crash database, traffic database).
- *Data handling protocols* – These protocols govern data extraction, data cleaning, transformation of the data into the warehouse format, loading the data into the data repository using a unified schema and the schedule with which data are refreshed.
- *Metadata* – The development and dissemination of metadata (i.e. data about data) supports the truth-in-data principle (see *Quality Assurance Tools*) and should be directed by metadata standards and customer needs (see *Generation of Metadata Tool* for additional details).
- *Analytical protocols* – These protocols may involve querying (custom or pre-defined), on-line analytical processing and various data mining and machine learning techniques.
- *Data products* – Common data products include tables, charts, maps, reports and special communications tools, such as Dashboards and Report Cards (see *Communication Tools*).

Figure 21: Schematic of common data warehousing architecture



Source: Adapted from Gharaibeh et al. (2017)

Data retention and storage protocols

The design of a data warehouse architecture involves establishing data retention and storage protocols. These protocols are critical to ensure the long-term availability of data. Relatively low-cost data storage options (including cloud storage) enable many transportation agencies to prolong their data retention periods—sometimes indefinitely—and to store data at an increased level of detail. Data providers should nevertheless consider the factors in the following checklist when establishing data retention and storage procedures.

- Do legal requirements dictate minimum data retention periods for certain types of data?
- Are there protocols to identify when storage media become obsolete?
- Are there processes in place to translate data from one storage media to another?
- Are data stored in a well maintained, backed up and secure data server?
- Have cloud-based computing and storage options been evaluated and leveraged?
- Are there protocols in place to notify data customers of potential data disposal?
- Have stored data been prioritized to guide decisions concerning data disposal?

Many agencies outsource data storage using cloud-based tools. The cost of using cloud-based tools is usually commensurate with storage size, but is typically economical relative to in-house options. Moreover, data security measures are normally included in cloud-based tools and data back-up is available as an add-on service. While there may be some concern about releasing data in this way, the benefits of cloud-based tools generally outweigh potential risks. Specifically, these benefits include:

- Integrated computing and storage (i.e. no need to distinguish computation and storage tasks)
- Ease of information provision (i.e. facilitates integration with web-based information delivery platforms)
- Scalable and customized computing and storage (i.e. enables an agency to right-size these functions in a flexible manner)
- Enabling an agency to focus on business delivery rather than on computing performance and data security issues

Customer data access control

An initial consideration in the reporting and dissemination of transportation data involves establishing customer data access protocols. Customer data access protocols define the types of data and reports that various customers should be able to access. The different categories of customers interested in accessing data, their wide-ranging data needs and the complex nature of transportation data influence the establishment of the data access protocols.

It is useful to consider two data access protocols. The first data access protocol is the least restrictive and encompasses all data customers, including the general public. The basis for this protocol is that, as taxpayers, the general public ultimately funds most public-sector transportation agency programs. Consequently, to an extent, the general public owns the program and should be given rightful access to the data produced by the programs. This ownership, however, does not absolve data providers of their responsibility to minimize the inappropriate application of the data. Typically, this protocol enables customers to access standard data products in the form of summary data tables, charts, reports, or maps (see the *Communication Tools*). To minimize the time spent responding to data requests, these products should be readily available via a website.

The second data access protocol enables customers to access data beyond what is normally available as a standard data product. Data providers should consider the following items when balancing the potentially competing obligations of enabling data access and minimizing the misuse of data:

- Users should be provided access to the most comprehensive data available while ensuring that these data is accurate and useable given the training and expertise of the requesting entity.
- There may be a discrepancy between the data requested and the data needed. Consequently, there is a need to train data providers to clarify data user needs.
- As data collection equipment enables more real-time measurement and monitoring capabilities, user demands for timely data access will increase. A principal challenge in the provision of real-time data is the inability to perform data validation (quality control) procedures on this data prior to public release. Thus, if requested, this data should be provided subject to certain limitations of use and appropriate disclaimers.
- Data users within the same category should be treated equally.
- Access provision should generally be regarded as an irreversible action. Users that become accustomed to data being available—in whatever format—will be negatively impacted if data accessibility is subsequently curtailed.
- To demonstrate responsiveness and enhance program transparency, a mechanism to track data requests should be established.

Generation of metadata

The truth-in-data principle (see the *Quality Assurance Tools*), is the impetus for generating and disseminating metadata. By adopting the truth-in-data principle, agencies commit to fully disclosing the metadata, analysis methods and data quality for all their data products. This recognizes that transportation data comes from different sources and have varying levels of quality which affect their application. It also supports meaningful data integration and sharing.

The following checklist presents metadata elements that should be considered. More detailed metadata standards should be consulted when generating metadata.

- Spatial location metadata
- Temporal period metadata
- Method of data collection (including equipment type and installation/maintenance history)
- Data cleaning, imputation and adjustment metadata
- Data quality metadata (see the Quality Assurance Tools for details about data quality dimensions)

In-house versus commercial off-the-shelf database management tools

A common data management decision pertains to the use of in-house versus commercial off-the-shelf (COTS) database management tools. In-house tools are typically constructed using readily-available computer programming platforms, coding languages and generic database software programs. COTS tools are software programs that can be installed with pre-determined settings and functions. Table 16 provides a comparison of in-house and COTS database management tools for four considerations: (1) setup and implementation efforts; (2) costs and resource requirements; (3) functionality and features; and (4) control.

Table 16: Comparison of in-house and commercial off-the-shelf (COTS) database tools

Consideration	In-house	COTS
Setup and implementation efforts		
Initial setup	Lengthy and challenging	Quick and easy
Compatibility with other databases	Higher	Lower
Costs and resource requirements		
Upfront costs	Higher	Lower
Ongoing costs	No annual fees but indirect maintenance and support costs	Usually annual subscription fee which includes maintenance and support
Technical expertise	Requires in-house staff that are responsible for maintenance and support	Most technical issues handled by vendor
Functionality and features		
User manual and documentation	Must be developed	Usually included
Graphing and mapping	Must be developed	Often included
User interface and experience	Sometimes difficult to operate and often lacks aesthetic appeal	Better user-friendliness and smoother operations
Control		
Flexibility and customization	Highly flexible and customizable	Limited flexibility and customizability
Data formats	Common	Often proprietary
Transparency	Fully transparent algorithms and methods	Often contains proprietary coding

B.1.5 GIS tools[18]

Overview

Transportation data is spatial in nature—that is, the data typically characterize a point, line (segments or networks), or area. Consequently, geographic information systems (GIS) are commonly used to analyze, manage, display and disseminate transportation data and to support performance-based decision making.

Many transportation agencies have adopted enterprise-level GIS to support their planning, design, construction, operations and management functions. Full-feature GIS software packages utilize a relational database platform that facilitates user-defined queries and data manipulation. Moreover, the spatial capabilities of the software enable queries and analyses based on the spatial relationships evident in the data.

Because transportation networks comprise linear features, the adoption of a standard linear referencing system (LRS) is critical to the successful integration of disparate spatial data that relate to a common transportation network. The LRS enables the positioning of a point (e.g. a traffic counter site) or linear feature by specifying its linear distance and direction from a known point on a network.

To help manage the integration of multiple datasets within a single LRS, most GIS software supports dynamic segmentation of an LRS. This enables attributes (concerning either points or line segments) to be stored and managed within the LRS without having to physically split the line in the database.

Advantages

- Enables effective visualization of spatial features and patterns.
- Reveals spatial relationships between disparate data sets that may not be apparent in other analytical environments.
- Fully-integrates the analytical capabilities of relational databases and associated querying, data mining and machine learning techniques.

Characteristics

Characteristic	Low	Med	High	Unable to assess
Effectiveness	☐	☐	☑	☐
Required level of commitment	☐	☐	☑	☐
Required level of expertise	☐	☐	☑	☐
Effort for implementation	☐	☐	☑	☐
Overall performance	☐	☐	☑	☐

Key sources

- Regehr et al. (2017)
- ArcGIS® resources

[18] Aspects of this tool are excerpted and/or adapted with permission from Regehr et al. (2017).

Disadvantages

- Enterprise-level GIS implementation requires extensive coordination across traditional business units or functional areas within a transportation agency.
- May not be immediately compatible with legacy design drawings and certain maps prepared as "space-less" graphics (e.g. drawings in Cartesian coordinates may not be easily referenced using geographic coordinates).
- Attribute data require periodic updates, which requires resources and coordination across business units.
- Spatial features, especially linear features within an LRS, require periodic maintenance (e.g. a highway realignment project may require adjustments to the LRS for multiple segments).

Examples of available software

There are numerous GIS software tools available on the market—both commercial and open-source. The following software programs were identified to illustrate the variety of tools available but have not been evaluated as part of this study. Practitioners interested in applying any of these software packages are encouraged to investigate their effectiveness prior to application.

ArcGIS®. A full-featured; commercial GIS software used by many transportation agencies that supports enterprise and desktop applications as well as on-line data dissemination through ArcGIS Online (AGOL®).

QGIS®. A powerful, open-source GIS software that supports cartographic and geospatial data processing with various analytical plug-ins.

AutoCAD® and Civil 3D®. AutoDesk® products that have transformed traditional CAD technologies into GIS-like tools, which orient design drawings in geographic space.

MicroStation. A three-dimensional CAD product designed to integrate with numerous other civil engineering products of Bentley Systems®.

B.2 Analysis and evaluation tools

B.2.1 Life-cycle cost analysis

Overview

Life-cycle cost analysis involves a realistic estimation of costs and benefits of a variety of projects. This method compares the "merit" of different projects on an equal basis by evaluating the total economic worth of the initial construction cost and discounted future maintenance and rehabilitation costs over the facility life cycle. A discount rate is used to estimate the present worth of future costs and benefits and proper economic analysis should include life cycle assessments of factors such as:

- Agency costs
- User costs and benefits
- Societal costs and benefits

Other project-level life-cycle benefits to consider include decreases in agency costs, reduction in vehicle operating costs, shortening of travel time, decreases in vehicle crashes and reduction of vehicle emissions.

Life-cycle cost analysis methods can be used to optimize decisions made for a single asset, or a network of assets. When completed on a single asset, optimal maintenance actions for a single asset are determined to ensure a given performance level over asset lifetime while minimizing costs and risks.

Models also exist to optimize network-wide performance of assets over a given time period using a single-asset life cycle composition for each asset and system-wide performance constraints. These include models used in multi-objective optimization (see the *Multi-Objective Optimization Tool* in this section).

All alternatives should be compared over the same life cycle, such that all factors can be forecasted to a reasonable degree of reliability. Ten years is the suggested upper limit for short-term projects, whereas 50 years or more is reasonable for longer-term projects such as bridges. The sensitivity of results to the discount rate used is an important consideration, especially for longer-term projects. A realistic assessment of economic conditions is required as a basis for objective inputs into the analysis.

Characteristics

Effectiveness

Low	Med	High	Unable to assess
☐	☑	☐	☐

Data needs

Low	Med	High	Unable to assess
☑	☐	☐	☐

Required level of expertise

Low	Med	High	Unable to assess
☑	☐	☐	☐

Effort for implementation

Low	Med	High	Unable to assess
☑	☐	☐	☐

Overall performance

Low	Med	High	Unable to assess
☐	☑	☐	☐

Key sources

- Uddin, Hudson and Haas (2013)
- Li and Madanu (2009)
- Bhargava et al. (2013)
- Al-Kathairi (2014)
- Haas et al (2014)
- Faghih-Imani and Amador-Jimenez (2013)
- Telephone interviews with agencies

Advantages

- Life-cycle cost analysis is perceived to be a reliable, objective and consistent technique for prioritizing investments.
- Life-cycle cost analysis is highly successful in identifying optimal pavement designs considering long-term pavement performance.
- Projects with different service lives and projects involving development in stages can be easily compared.
- All monetary costs and benefits can be expressed as a single value and in equivalent present-day terms, for ease of comparison.
- Non-monetary costs and benefits can be evaluated.
- The answer is expressed as a total payoff for the project, resulting in simple terms.
- The method is computationally simple and straightforward.
- Many performance measures used for assessing public assets are at the core of life cycle assessment and therefore facilitate the use of this method.

Disadvantages

- Life-cycle cost analysis cannot be applied to project alternatives where costs and benefits cannot be easily estimated.
- Results are often given in a “lump sum” format which may be more difficult to understand than other methods such as annual cost or internal rate of return.
- Life-cycle cost analysis produces a large dollar amount when considering overall life cycles, which may be a deterrent to investments if not properly understood.
- Often, models based on life-cycle cost analysis tend to monetize indicators associated with conflicting objectives to achieve a common unit of comparison. Such models can lose sight of the performance of individual objectives over time, such as environmental impacts.

Examples of available software

The following software programs were identified through the literature review but have not been evaluated as part of this study. Practitioners interested in applying any of these software packages are encouraged to investigate their effectiveness prior to application.

RealCost. Developed by the U.S. Federal Highway Administration (FHWA) to support the application of life-cycle cost analysis in the pavement project-level decision-making process.

BridgeLCC. Life-cycle costing software developed by the National Institute of Standards and Technology (NIST) to analyze cost-effectiveness of new, alternative materials for bridge projects.

TransAM. Open-source, license-free software developed via a partnership between the U.S. Federal Transit Administration (FTA) and transit authorities for Virginia and Pennsylvania; allows cataloging asset inventory, life-cycle cost analysis and report generation.

Transit Economic Requirements Tool (TERM) Lite. Microsoft Access-based software developed by the U.S. FTA with input from transit agencies in Chicago, Los Angeles and San Francisco; allows users to identify life-cycle costs for transit assets including vehicles, stops, garages and other facilities.

B.2.2 Present worth

Overview

Present worth (PW) is a concept for considering future cash flows as if they were due today. The key concept in PW is the time value (or investment potential) of money. Funds in-hand today can be invested and gain value over time and are thus worth more than funds of the same amount that are only available at some time in the future.

When applied to asset management, PW concepts can allow projects or programs with varying cash flow timelines to be compared with each other in present terms. The basic equation to convert a future cash flow to PW is:

$$PW = \frac{C}{(1+i)^n}$$

Where *C* is the amount of the future cash flow, *i* is the interest rate and *n* is the number of periods into the future when the cash flow is due. This concept can be applied to future costs (negative *C* values) and future benefits (positive *C* values).

The interest rate used in the PW equation can be a simple rate selected by the agency based on financial conditions and/or the agencies valuation of investments. Alternatively, the equation can use a discount rate, equal to the interest rate minus the rate of inflation. Use of a discount rate—rather than a simple interest rate—can be useful in scenarios where, for example, construction costs are increasing quickly.

In order to use PW concepts, agencies should have information on the timing and future value of cash flows (credits and/or obligations), along with an interest rate (or discount rate) for the time period in question.

Present worth concepts are key inputs to the other analysis and evaluation tools in this toolkit.

Characteristics

Effectiveness

☑ Low ☐ Med ☐ High ☐ Unable to assess

Data needs

☑ Low ☐ Med ☐ High ☐ Unable to assess

Required level of expertise

☑ Low ☐ Med ☐ High ☐ Unable to assess

Effort for implementation

☑ Low ☐ Med ☐ High ☐ Unable to assess

Overall Performance

☑ Low ☐ Med ☐ High ☐ Unable to assess

Key sources

- Uddin, Hudson and Haas (2013)

Advantages

- Can compare projects with different timelines and/or phasing using consistent units
- Simple, understandable implementation
- Can be expanded to consider inflation
- Can be used as an input to more sophisticated tools

Disadvantages

- Requires benefits and costs to be quantified; may be difficult to account for qualitative benefits and costs
- Limits comparisons to inputs provided by the user; does not include methods for identifying project externalities and/or interaction between projects

Examples of available software

The following software programs were identified through the literature review but have not been evaluated as part of this study. Practitioners interested in applying any of these software packages are encouraged to investigate their effectiveness prior to application.

Microsoft Excel. Ubiquitous spreadsheet software allowing users to implement the PW equation shown on the previous page.

TransAM. Open-source, license-free software initially developed via a partnership between the U.S. Federal Transit Administration (FTA) and transit authorities for Virginia and Pennsylvania; web-based software allows cataloging asset inventory, Present Worth calculations and report generation.

Transit Economic Requirements Tool (TERM) Lite. Microsoft Access-based software developed by the U.S. FTA with input from transit agencies in Chicago, Los Angeles and San Francisco; allows users to conduct PW analyses for transit assets including vehicles, stops, garages and other facilities.

B.2.3 Internal rate of return on investment

Overview

The internal rate of return (IRR) method determines the interest rate at which the costs and benefits of a project are equal. It could be estimated using equivalent uniform annual costs or the present worth of costs and benefits.

The rate of return of a candidate project is compared to the standard alternative, as well as to other alternatives. This series of comparisons will eliminate all but one alternative – the one having the highest rate of return.

In order to use IRR, agencies should have information on the timing and future value of cash flows (credits and/or obligations) for each alternative to be compared.

Advantages

- Easily understandable and comprehensible

Disadvantages

- Focuses on monetary values and thus difficult to assess intangible benefits

Examples of available software

The following software programs were identified through the literature review but have not been evaluated as part of this study. Practitioners interested in applying any of these software packages are encouraged to investigate their effectiveness prior to application.

Microsoft Excel. Ubiquitous spreadsheet software that includes an “IRR” function that calculates IRR based on cash flows that occur at regular intervals; an “XIRR” function returns IRR for cash flows at regular or irregular intervals.

AgileAssets. Asset management software for planning and analysis, as well as operations management, that includes functions for IRR, trade-off analysis and cross-asset optimization; can consider transit assets including vehicles, stops, garages and other facilities.

Characteristics

	Low	Med	High	Unable to assess
Effectiveness	☐	☑	☐	☐
Data needs	☑	☐	☐	☐
Required level of expertise	☑	☐	☐	☐
Effort for implementation	☑	☐	☐	☐
Overall performance	☐	☑	☐	☐

Key sources

- Uddin, Hudson and Haas (2013)

B.2.4 Incremental benefit-cost and cost-effectiveness

Overview

Incremental benefit-cost (B/C) method. Benefit-cost (B/C) is the ratio of benefits and costs of a project, either in terms of present worth or equivalent uniform annual worth (i.e. annual cash flow). The B/C method is widely used for infrastructure projects, particularly for large projects.

Often, alternatives with B/C ratios greater than 1.0 are compared on an incremental basis. This involves calculating the B/C ratios on increments of expenditures and investments for successively higher-cost alternatives. The initial increment considered is that of going from a do-nothing option to the first feasible option. If the incremental B/C ratio is greater than 1.0, the assessed alternative becomes the base of the next increment. This pair-wise comparison is repeated until all alternatives have been examined.

The incremental B/C method is a near-optimization method used to draw comparisons among a set of proposed alternatives. It is used when there is no requirement to fix costs or benefits and thus, differences between alternatives are examined.

Cost-effectiveness (CE) method. Cost-effectiveness (CE) is the ratio of the effectiveness of an alternative divided by the present worth of costs over the life of a facility. The effectiveness of an alternative is calculated as the area under a performance curve multiplied by traffic volume and the length of the road section. CE values are expressed as indexes and thus should only be used for comparison purposes. The CE method, like the incremental B/C method, is a near-optimization method involving the following steps:

1. Consider each of a set of possible strategies (combinations of possible alternatives across the asset network).
2. Calculate the CE of each strategy.
3. Select strategy resulting in the best CE, within budget constraints.
4. Compare all other strategies to the one with the best CE, by means of calculating the marginal (incremental) CE; if the marginal CE is negative then the strategy is removed from consideration and if the marginal CE is positive then it replaces the initial strategy.
5. Repeat until all strategies have been exhausted.

Characteristics

Characteristic	Low	Med	High	Unable to assess
Effectiveness	☐	☑	☐	☐
Data needs	☑	☐	☐	☐
Required level of expertise	☑	☐	☐	☐
Effort for implementation	☑	☐	☐	☐
Overall performance	☐	☑	☐	☐

Key sources

- Uddin, Hudson and Haas (2013)
- Khurshid et al. (2011)
- Amin and Amador (n.d.)
- Telephone interviews with agencies

CE compares the money spent on a program to benefits gained as a result of the program. The benefits can be measured in terms of monetized or non-monetized measures of effectiveness. Costs consist of agency, user, capital and life-cycle costs.

The CE method is extensively used in the pavement field as a convenient way to compare alternatives with varying performance trends.

Advantages

- Provides a relatively straight-forward calculation where costs and benefits are clearly outlined
- Successful in evaluating the cost-effectiveness of individual system interventions
- Perceived to be a reliable, objective and consistent technique for prioritizing investments

Disadvantages

- Difficult to assess intangible benefits in some important categories such as safety, congestion, pollution and social cost.
- Challenges arise when costs and benefits are not easily categorized and are not incurred/enjoyed by the same stakeholders.
- Incremental B/C method compares alternatives one at a time and cannot consider more than two alternatives at the same time or situations where the performance of alternatives is interrelated.

Examples of available software

The following software programs were identified through the literature review but have not been evaluated as part of this study. Practitioners interested in applying any of these software packages are encouraged to investigate their effectiveness prior to application.

MicroBENCOST. Designed to analyze different types of highway improvement projects in a corridor at the operational level.

StratBENCOST. Designed to support multi-year strategic planning and budgeting by assisting with the comparison of large numbers of project options in a jurisdiction, including project options in the concept stage (the difference between this software and MicroBENCOST is the application – this is for strategic planning and budgeting while MicroBENCOST is applied to operational planning and budgeting questions).

Highway Pavement Management Application (HPMA). Software proprietary to Stantec; uses pavement condition data and analysis models to forecast maintenance and rehabilitation needs across the road network and can develop maintenance program budgets and priorities.

Transit Economic Requirements Tool (TERM) Lite. Microsoft Access-based software developed by the U.S. FTA with input from transit agencies in Chicago, Los Angeles and San Francisco; allows users to conduct transit system benefit-cost analyses for assets including vehicles, stops, garages and other facilities.

B.2.5 Risk assessment and risk management

Overview

Risk assessment and risk management are tools to help agencies understand their exposure to risk and how best to manage that exposure.

Risk assessment identifies risks and measures or forecasts risk probability and severity. Software can be used to consider how risks can be interrelated between assets, such that failure of one asset may precipitate premature the failure of other assets.

Risk management identifies strategies to address risks and identifies the costs of implementing those strategies. Risk management should follow risk assessment, as risks first need to be identified and understood before strategies can be developed to address those risks. With the information from the risk assessment process, strategies for addressing risks can be evaluated and trade-offs can be identified between different strategies and funding levels. This can allow agencies to make informed decisions on how best to manage risks.

Risk assessment and risk management can be applied at the project level and/or at a program or organization level. Information on risks and strategies to address risks can also be used as inputs to cross-asset optimization and multi-objective optimization tools (see the *Cross-Asset Optimization Tool* and the *Multi-Objective Optimization Tool* in this section).

In order to use risk assessment and risk management tools, agencies should have a clear understanding of their strategic goals and what risks might impact their ability to meet these goals. Agencies should also have data on the existing condition of their assets, an outline of the range of realistic funding scenarios (particularly related to asset maintenance) and an understanding of how tolerable different risks are to the agency and the people they serve.

The following key questions should be asked during the risk assessment and risk management processes:

- What can go wrong?
- What is the probability that it will go wrong?
- What are the consequences associated with the failure?
- What can be done to mitigate the risk?
- What are the associated trade-offs with respect to costs, benefits and risks?
- What are the impacts of current management decisions on future options?

Characteristics

Characteristic	Low	Med	High	Unable to assess
Effectiveness	☐	☐	☑	☐
Data needs	☐	☑	☐	☐
Required level of expertise	☐	☐	☑	☐
Effort for implementation	☐	☑	☐	☐
Overall Performance	☐	☑	☐	☐

Key sources

- Mohseni et al. (2017)
- Maggiore & Ford (2015)
- Boadi et al. (2015)
- AASHTO (2013)
- Boadi and Amekudzi (2013)
- Amekudzi and Meyer (2011)

Optimal allocation of resources can be assisted by applying the following framework across asset classes:

- Include risk mitigation objectives when developing overall agency goals and objectives
- Develop risk assessment scores as a function of probability and consequence and include these as performance measures within asset management frameworks
- Identify projects which will help mitigate deteriorating structural performance and consider the uncertainty of costs and benefits
- Determine the "must-do" projects (i.e. those projects that pose unacceptably high risks if not selected)
- Assess the financial risk of alternative funding scenarios

The U.S. Department of Transportation has collaborated with the Navy and Coast Guard to implement a risk-based metric that links facilities to program missions. This metric uses operational risk management techniques of probability and severity and applies them to a facility to determine how the system would function if there are interruptions to that facility. The following questions guide the risk assessment for each functional element (in the case of asset management, each asset or components of the asset):

- How long could the "functions" supported by the facility (functional element) be stopped without adverse impacts to the overall objectives?
- If the facility were no longer functional, could the agency continue performing its mission by using another facility, or by setting up temporary facilities (i.e. are there workarounds)?
- How long could the services provided by the agency be interrupted before impacting performance and overall goals?
- How difficult would it be to replace or replicate the services provided by the agency with another provider from any source before impacting the agency's goals?

Advantages

- Can direct resources to where they can have maximum impact at addressing risks to assets and the system/organization as a whole
- Can address risks proactively, rather than reactively
- Applies at various scales based on agency goals and available resources
- Identifies how different funding levels impact risk exposure
- Helps technical staff communicate risks to decision makers

Disadvantages

- Only considers agency objectives that involve risks
- Can overlook or undervalue qualitative risks that are hard to quantify
- Can be difficult to identify and account for externalities related to asset failure and thus to fully quantify risk severity
- Asset deterioration curves used in the absence of locally adjusted, historical data may not reflect actual asset performance
- Effectiveness of risk management strategies—relative to other factors—may not be well understood and strategies applied in the present and future may perform differently than in the past

Examples of available software

The following software programs were identified through the literature review but have not been evaluated as part of this study. Practitioners interested in applying any of these software packages are encouraged to investigate their effectiveness prior to application.

Resolver Risk Management Software. Customizable software that allows users to summarize risks across their assets and provides tools to identify risk control measures that will have the largest impact.

Fusion Framework. Software suite that provides tools to aggregate and summarize risk data, develop risk management measures and track progress with key performance indicators.

Project Risk Manager. Cloud-based software with functions for project-level risk assessment and risk management; includes a directory of common risks to help identify project-specific risks; a free version offers many functions of the paid version.

B.2.6 Cross-asset optimization

Overview

Cross-asset optimization (CAO) is a tool to help agencies allocate resources across asset classes. Traditionally, resources are allocated based on precedent and/or engineering judgement. This approach is likely sub-optimal in that decision making is exposed to the biases of decision makers and precedents may be outdated and not representative of contemporary priorities.

Modern CAO tools typically use a Delphi approach and/or a multi-objective decision analysis (MODA) approach.

In a Delphi approach, resource allocation decisions are made by a committee of agency decision makers and experts (either internal to the agency or from a third party) from different subject areas. The approach uses an iterative process to forecast outcomes of different resource allocation decisions and then refine decision making until a consensus is reached.

A MODA approach has many similarities with multiple-objective optimization approaches (see the Multi-Objective Optimization Tool). Optimal resource allocation decisions can be identified considering multiple interrelated and/or conflicting objectives. The MODA approach can be conducted in a top-down or bottom-up fashion.

In a top-down approach, program level trade-off analysis is conducted to identify funding levels based on how each asset or program will respond to a given funding level. The responses (i.e. performance) are used to create response curves, showing performance measures as a function of the funding level. Projects are then prioritized based on the level of funding available for that asset and the ability to satisfy the goals identified for that asset or program.

In a bottom-up approach, a set of projects are selected from potential projects spanning all assets, which maximize the overall measure of performance (i.e. utility). The trade-off analysis is conducted at the project level. Unlike the top-down approach, there are no direct results showing the implications of the level of funding applied to an asset class. This approach can have technical challenges associated with developing robust and universal algorithms and the collection of quality data.

Both approaches can provide insight into how projects or asset classes can perform at different funding levels, how projects can affect multiple objectives and how projects can have different effects when combined with each other.

Characteristics

Effectiveness

☐ Low ☐ Med ☑ High ☐ Unable to assess

Data needs

☐ Low ☐ Med ☑ High ☐ Unable to assess

Required level of expertise

☐ Low ☐ Med ☑ High ☐ Unable to assess

Effort for implementation

☐ Low ☐ Med ☑ High ☐ Unable to assess

Overall performance

☐ Low ☐ Med ☑ High ☐ Unable to assess

Key sources

- Spy Pond Partners (2019)
- Bryce et al. (2018)
- Porras-Alvarado et al. (2016)
- Maggiore & Ford (2015)
- Fwa and Farhan (2012)
- Geiger et al. (2005)

Agencies can implement the following framework, which uses similar themes to the MODA approach but leans toward a more finance-oriented perspective:

- *Use the agency's goals and objectives to guide its priorities* – The framework begins with strategic planning, including goals, resource allocation philosophy and objectives which govern the operation and performance measurement of agencies.
- *Categorize various assets* – In this step, assets are identified in terms of a physical asset class, asset ownership and other relevant information (e.g. urban versus rural, functional class, traffic volume, usage type).
- *Develop performance metrics to evaluate progress toward goals and objectives and assess performance* – The objective is to evaluate the condition of the infrastructure system, to generate an overall score for each of the assets being analyzed. An asset performance prediction model is essential for predicting asset value conditions in the future. As part of this step, performance-funding relationships should be developed and used to measure the effects of funding levels on overall condition scores for each asset. Transportation agencies can use historical funding and performance data to develop and calibrate the asset performance models.
- *Apply decision science (the approach that guides the selection of alternatives through weighting, scaling, scoring, prioritization and optimization techniques) to score differing projects on a level playing field* – Selection is optimized based on the relative importance of benefits to the decision maker, often based on the expected value of a project per dollar spent.
- *Conduct trade-off analysis to refine scenario planning and to compare priorities with fiscal constraints* – Optimization accounts for fair allocation of budget to investment categories in relation to the total available budget. In a transportation asset management decision-making context, there are often multiple objectives that need to be achieved and fair allocation is important. In general, there are three categories of equity that should be considered in transportation funding allocation: rate of return, performance and need:
    - *Rate of return* – Programs should receive the same percentage of resources as they contribute.
    - *Performance* – This is concerned with the allocation of resources between programs or districts that differ in performance or condition. Funding allocation policies are considered equitable if they favour conditionally disadvantaged programs, therefore compensating for overall inequities.
    - *Need* – This concept is used to support allocation based on demand, which means that resources should be allocated according to the actual needs of different programs or districts.

Advantages

- Considers performance against multiple, diverse, potentially interrelated and/or conflicting objectives
- Compares overall impact of projects in different asset classes
- Illustrates how different levels of funding enable or hinder the achievement of policy goals
- Identifies trade-offs present at various funding levels

Disadvantages

- Requires careful definition of optimization functions, which can be difficult when many variables exist
- Complex optimization function definitions can make it difficult for stakeholders to understand the analysis
- Reliability of evaluations depends on how accurately project impacts are assessed against each criterion
- Requires subject-matter experts from many fields

Examples of available software

The following software programs were identified through the literature review but have not been evaluated as part of this study. Practitioners interested in applying any of these software packages are encouraged to investigate their effectiveness prior to application.

Asset Optimizer. Cloud-based software-as-a-service (SaaS) application accessible from a web browser. Algorithms generate risk-based, system-wide multi-year asset renewal plans. Optimization settings can be tweaked to maximize network-level condition improvement, minimize risk, or minimize life-cycle costs. Output can help users to assess how funding levels and investment strategies impact risk at the level of individual assets, asset classes and the entire system.

Cross-Asset Resource Allocation Tool. Spreadsheet or web-based tool initially developed as part of an NCHRP project, allowing users to set weights for various objectives and optimize resource allocation based on scoring.

AgileAssets. Asset management software for planning and analysis, as well as operations management. Includes functions for internal rate of return on investment, trade-off analysis and cross-asset optimization and can consider transit assets including vehicles, stops, garages and other facilities.

B.2.7 Multi-objective optimization

Overview

Multi-objective optimization is an evaluation tool that considers how candidate projects or programs perform against multiple criteria. This can help agencies to identify how projects and programs affect the achievement of policy goals, which options are the best to consider and how funding constraints limit options and potential outcomes. Projects and programs can be compared against each other individually, or in packages that are either defined by the user or generated by the analysis software. Comparisons can be made both within and between asset classes.

The analysis uses a mathematical optimization function for each criterion and a separate overall optimization function considering performance against all the criteria. The output is either a single "optimum" solution or a set of "acceptable" solutions.

There are multiple approaches to formulating individual criteria and the overall optimization function. Individual criteria are typically formulated as a threshold (e.g. proportion of structurally deficient bridges to not exceed 25%), an average (e.g. the network's average collision rate), or a sum over the network (e.g. total tonnage of pollutant emissions, total number of jobs created, transit service hours). Cost can be considered as an independent criterion—which includes some consideration for the benefits of incrementally less expensive projects—or as a constraint, which screens out projects that exceed the threshold, but does not consider incremental cost savings.

Methods for the overall optimization function include Pareto solutions and weighting. Pareto solutions identify the set of alternatives that cannot be improved with respect to one criterion without degrading performance for other criteria. Pareto solutions are helpful where there are not agreed upon relative weights for the criteria. If criteria are weighted, alternatives can be scored and ranked accordingly. Each alternative's score is the sum of the products of the criteria scores and weighting factors. Weights are usually calibrated to reflect stakeholder preference.

Agencies have used multi-objective optimization to prioritize road sections for pavement maintenance. Research has largely focused on applications for pavements and bridge assets, but the process can be applied to other assets. For example, one study used multi-objective optimization to identify strategies to optimize transit fleet quality and economic performance, using data from the Michigan Department of Transportation.

Characteristics

Characteristic	Low	Med	High	Unable to assess
Effectiveness	☐	☐	☑	☐
Data needs	☐	☐	☑	☐
Required level of expertise	☐	☑	☐	☐
Effort for implementation	☐	☐	☑	☐
Overall performance	☐	☐	☑	☐

Key sources

- Bai et al. (2015)
- Maggiore & Ford (2015)
- Bhargava et al. (2013)
- Wu et al. (2012)
- Cambridge Systematics (2005)
- Cambridge Systematics (2003)

Advantages

- Considers performance against multiple, diverse, potentially interrelated and/or conflicting criteria
- Compares overall impact of projects in different asset classes
- Illustrates how different levels of funding enable or hinder the achievement of policy goals
- Identifies trade-offs present at various funding levels
- Weighting can be tuned to match stakeholder priorities

Disadvantages

- Requires careful definition of optimization functions; this can be difficult in the presence of many variables
- Complex optimization function definitions can make it difficult for stakeholders to understand the analysis.
- Reliability of evaluations depends on how accurately project impact is assessed against each criterion.
- If stakeholders do not reach consensus on the relative weighting of criteria, "optimal" solutions may not be accepted by all stakeholders.

Examples of available software

The following software programs were identified through the literature review but have not been evaluated as part of this study. Practitioners interested in applying any of these software packages are encouraged to investigate their effectiveness prior to application.

Evolver. Microsoft Excel-based software that employs several algorithms to arrive at an overall optimal solution. Often applied to industrial-type problems (e.g. scheduling, inventory management) as well as transportation asset management.

AssetManager NT & PT. Developed as part of NCHRP Report 545 (2005), AssetManager is intended to be a suite of tools for analyzing transportation asset tradeoffs. The "NT" (Network Tool) tool is focused on longer-term (10- to 20-year) network-level trade-offs, while the "PT" (Project Tool) tool is focused on program-level (1- to 3-year) trade-offs.

Transit Economic Requirements Tool (TERM) Lite. Microsoft Access-based software developed by the US FTA with input from transit agencies in Chicago, Los Angeles and San Francisco. Allows users to conduct transit system multi-objective optimization analyses considering five commonly used criteria plus a sixth, custom criterion; also allows users to set custom weights for each criterion.

B.3 Communication tools

B.3.1 Dashboards

Overview

Dashboards are tools to present data about the state of a system over a period of time, or at a certain point in time. They are typically used to present data relevant to managing day-to-day operations. The presentation is often visually oriented, with more graphs and charts than tables or blocks of text.

Examples of data included on dashboards include the total kilometres of road by pavement condition rating, bridge superstructure condition rating, transit schedule adherence a given time period and others.

Dashboards often allow users to "drill down" into summary data to gain deeper insights from base data. For example, a transit schedule adherence summary table may show data aggregated over the entire system, but it may also allow users to identify individual routes with poor schedule adherence.

Dashboards are like report cards, but the two tools differ in purpose. Dashboards are for presenting information required for making day-to-day management decisions. Report cards are for tracking progress towards goals and making longer-term strategic decisions. Depending on an agency's goals and structure of operations, there may be some overlap between the information presented on a dashboard and on a report card.

In order to use dashboards, agencies should have a clear understanding of which metrics they want to present and a data collection and management system that can report data in a consistent format.

Advantages

- Provides an intuitive summary of system conditions at a point in time, or over an interval of time
- Helps technical staff communicate with decision makers and the public

Disadvantages

- Effort may be required to organize data into a standard format before inputting to a dashboard.
- Ongoing use of a dashboard may require changes to data collection, storage and formatting processes.

Characteristics

Characteristic	Low	Med	High	Unable to assess
Effectiveness	☐	☑	☐	☐
Data needs	☐	☑	☐	☐
Required level of expertise	☑	☐	☐	☐
Effort for implementation	☑	☐	☐	☐
Overall performance	☐	☑	☐	☐

Website references

- Clearpointstrategy.com
- Rw3.com
- Tableau.com
- Sisense.com
- Klipfolio.com

Examples of available software

The following software programs were identified through the literature review but have not been evaluated as part of this study. Practitioners interested in applying any of these software packages are encouraged to investigate their effectiveness prior to application.

Microsoft Excel. Ubiquitous spreadsheet software allows users to create custom dashboards with built-in charting tools; interactive dashboards require advanced knowledge.

Tableau. Intuitive interface for creating interactive dashboards with tools for connecting to data in various formats and cleaning and organizing for presentation; offers Desktop, Cloud and Mobile options.

Sisense. Platform allowing users to create their own dashboard applications and to use artificial intelligence to find insights from data; includes tools for connecting to various data formats.

Klipfolio. Allows data to be imported from various sources and in various formats; users can create custom interactive dashboards and are typically from businesses rather than public agencies.

B.3.2 Report cards

Overview

Report cards are tools to present data on progress towards goals. They are typically used to present data relevant to strategic decision making. The presentation can use visuals such as charts, but it often also includes tables and text.

Examples of data summarized on report cards include tables showing system-wide collision counts compared to a target value, transit on-time performance compared to a target and pavement maintenance projects completed relative to a target.

Report cards can include commentary to explain if the agency is on-track to achieve its goals. Commentary can also explain how changes to strategies have affected results.

Report cards are like dashboards, but the two tools differ in purpose. Report cards are for tracking progress towards goals and making longer-term strategic decisions. Dashboards are for presenting information required for making day-to-day management decisions. Depending on an agency's goals and structure of operations, there may be some overlap between the information presented on a report card and on a dashboard.

In order to use report cards, agencies should have identified performance measures with which to track progress towards goals and a data collection and management system that can report data in a consistent format.

Advantages

- Provides a summary of how well the agency is progressing towards achieving its goals
- Helps technical staff to communicate results and the need for strategic change to decision makers

Disadvantages

- Requires a clear understanding of how performance measures relate to agency goals
- Report cards may require changes to data collection, storage and formatting processes

Characteristics

Characteristic	Low	Med	High	Unable to assess
Effectiveness	☐	☑	☐	☐
Data needs	☐	☑	☐	☐
Required level of expertise	☑	☐	☐	☐
Effort for implementation	☑	☐	☐	☐
Overall performance	☐	☑	☐	☐

Website references

- Clearpointstrategy.com
- Rw3.com
- Tableau.com
- Sisense.com
- Klipfolio.com

Examples of available software

The following software programs were identified through the literature review but have not been evaluated as part of this study. Practitioners interested in applying any of these software packages are encouraged to investigate their effectiveness prior to application. Because of the similarity between dashboards and report Cards, many of the typical available software can be used to deliver both.

Microsoft Excel. Ubiquitous spreadsheet software allowing users to create custom report cards with built-in table and chart tools; interactive report cards require advanced knowledge.

Tableau. Intuitive interface for creating interactive report cards with tools for connecting to data in various formats and cleaning and organizing for presentation; offers Desktop, Cloud and Mobile options.

Sisense. Platform allowing users to create their own report card applications, using artificial intelligence to find insights from data; includes tools for connecting to various data formats.

Klipfolio. Allows data to be imported from various sources and in various formats; users can create custom interactive report cards and are typically from businesses rather than public agencies.

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Appendix A – Survey questionnaire

The Transportation Association of Canada is currently undertaking a project to identify lessons learned and develop a practitioner's toolkit for performance-based decision making. This survey is a component of a project intended to gain practical knowledge from across Canada about the development and use of performance-based approaches in decision making, particularly within the context of asset management.

We ask for your assistance by taking 15 minutes of your time to complete this survey on behalf of your agency. Thank you for your participation.

1. ***Contact information***

2. ***What type of agency do you represent? (check one)***
   - Municipality
   - Province
   - Federal Government
   - Utility
   - Transportation authority or association (e.g. Ontario Good Roads Association (OGRA), Metrolinx, Metropolitan Regional Transportation Authority, TransLink)
   - Other (please specify in text box)

3. ***For which of the following asset classes does your agency have an asset management program in place? (select all that apply)***
   - Pavements
   - Bridges
   - Culverts
   - Paths and sidewalks
   - Transit
   - Signs, signals and traffic control devices
   - Streetlights
   - Geotechnical assets (e.g. dikes, retaining walls)
   - Subsurface infrastructure (e.g. sewers, water pipes)
   - Other (please specify in text box)

4. ***Based on the assets you identified in Question 3, what is your satisfaction level with your agency's current asset management practices and procedures? (check one for each)***
   - Very satisfied
   - Somewhat satisfied
   - Somewhat dissatisfied
   - Very dissatisfied
   - Do not know

5. ***What is the reason for the level of satisfaction or dissatisfaction you identified? (select all that apply)***
    - Currency
    - Completeness
    - Data quantity
    - Data quality
    - Data availability
    - Software capabilities
    - Staff turnover
    - Institutional knowledge
    - Other

Repeat Questions 4 and 5 for each asset class selected in Question 3.

6. ***Which of the following tools support your agency's asset management program? (select all that apply)***
    - No support tools
    - Off-the-shelf asset management software (please specify in text box)
    - Tailored off-the-shelf asset management software (please specify in text box)
    - In-house asset management software (please specify in text box)
    - GIS tools (please specify in text box)
    - Other (please specify in text box)

7. ***Which of the following non-traditional or intangible asset classes are included in your asset management program? (check all that apply)***
    - Data
    - Human capital
    - We do not include intangible asset classes in our asset management program
    - Other (please specify in text box)

8. ***Does your agency implement cross-asset optimization in its asset management program?***
    - Yes
    - No
    - Don't know (same path as no)

9. ***If yes to question 8, which asset classes are considered together?***

10. ***What optimization techniques does your agency use for managing assets and what is your level of satisfaction with each technique? (select all that apply and indicate satisfied, somewhat satisfied, somewhat dissatisfied, dissatisfied and do not know)***
    - We do not use optimization techniques
    - Engineering judgement
    - Worst-first

- Level-of-service targets
- Life-cycle present worth
- Benefit-cost
- Incremental benefit-cost
- Internal rate of return on investment
- Risk exposure (probability of failure and associated consequences)
- Multi-criteria or trade-off analyses (e.g. six sigma, linear programming, weighted sum, multi-attribute utility theory, superiority/inferiority ranking, analytic hierarchy process) (text box: Provide a brief description)
- Other x 5 (please specify in text box)

11. ***Is your agency's asset management program part of a broader performance-based framework?***
    - Yes
    - No
    - Don't know

12. ***Identify the level of impact of the following performance objectives on your agency's asset management decisions (beside each provide a check box for: high, moderate, slight, no impact, do not know).***
    - Asset condition
    - Quality of service
    - Mobility
    - Reliability
    - Productivity (e.g. level of use)
    - Safety
    - Environmental sustainability
    - Financial resources
    - Economic benefit
    - Risk mitigation
    - Liveability
    - Other (please specify in text box)

13. ***Which of the following does your agency measure (check one box, provide text box for each checked box)?***
    - Program inputs (resources used - e.g. dollars invested, personnel and equipment) (provide example)
    - Program outputs (scale of activity performed - e.g. kilometres of paved roads, % deficient bridges) (provide example)
    - infrastructure condition) (provide example)
    - Program outcomes (e.g. level of service, level of safety, reduction in emissions, liveability)
    - Do not know

14. To what extent would the following be beneficial to your agency for performance-based decision making? (options: not beneficial, somewhat beneficial, highly beneficial, do not know)

- Tools that evaluate investment levels and trade-offs
- Tools that identify needs and solutions
- Tools that compare options
- Tools that monitor results
- Tools for data management
- Tools for cross-asset optimization
- Tools to specify software requirements
- Other x 3

15. What is your agency's biggest challenge in allocating available financial resources to transportation infrastructure asset management? (please specify in text box)