MULTI-ATTRIBUTE UTILITY THEORY APPROACH TO VALUE-BASED INFRASTRUCTURE ASSET MANAGEMENT

Alyami, Zaid[1,3], and Tighe, Susan L.[2]

[1] PhD Candidate, Civil Engineering, University of Waterloo, Waterloo ON, Canada

[2] Professor and Norman W. McLeod Professor in Sustainable Pavement Engineering, Canada Research Chair. Director, Centre for Pavement and Transportation Technology Department of Civil and Environmental Engineering, University of Waterloo, Waterloo, ON, Canada

[3] zalyami@uwaterloo.ca

Abstract: Several government regulatory bodies mandate agencies to report their Capital Tangible Assets' (CTA) values within their annual statement. For example, the Canadian Public Sector Accounting Board (PSAB), the Governmental Accounting Standard Board (GASB) and the New Zealand International Financial Reporting Standards (NZ IFRS) to name a few. Using asset valuation financial/ accounting methods alone in reporting asset values may result in underestimating asset values. If the underestimated asset values are used as the basis of annual fund allocation, it may result in insufficient funding to preserve assets and therefore impact the overall network performance. Therefore, it is essential to integrate asset value in asset management systems to effectively manage assets while maintaining or enhancing the value of these assets. This paper introduces a Multi-Attribute Utility-Theory (MAUT) and optimization methodology that integrates asset value as a performance measure in infrastructure network-level asset management decision making. A case study using data from Ministry of Transportation Ontario (MTO) Pavement Management System (PMS2) is used to illustrate the proposed methodology.

1   Background

Transportation infrastructure assets typically represent the largest components of capital infrastructure assets. Canada has over 1,000,000 km of roads with the national highway system composed of 38,000 km of important provincial and national highways (Canada 2012; TAC 2013). On the other hand, the Canadian Infrastructure Report Card reported that 40% of roads are in fair, poor and very poor condition (Canadainfrastructure 2016).

The challenge of reduced budget, aging and deteriorating infrastructure, increasing traffic loading, increases the demand for implementing effective asset management to manage infrastructure assets cost effectively at acceptable LOS (Alyami and Tighe 2016).

There are many definitions of Asset Management in the literature; however, a widely used definition is that of the Federal Highway Administration (FHWA) US department of Transportation (FHWA 1999) also adopted by Transportation Association Canada (TAC) (FHWA 1999; TAC 1997, 2013)

> "Asset management is a systematic process of maintaining, upgrading and operating physical assets cost-effectively. It combines sound business practices and economic theory, and it provides tools to facilitate a more organized logical approach to decision making. Thus, asset management provides a framework for handling both short- and long-range planning."
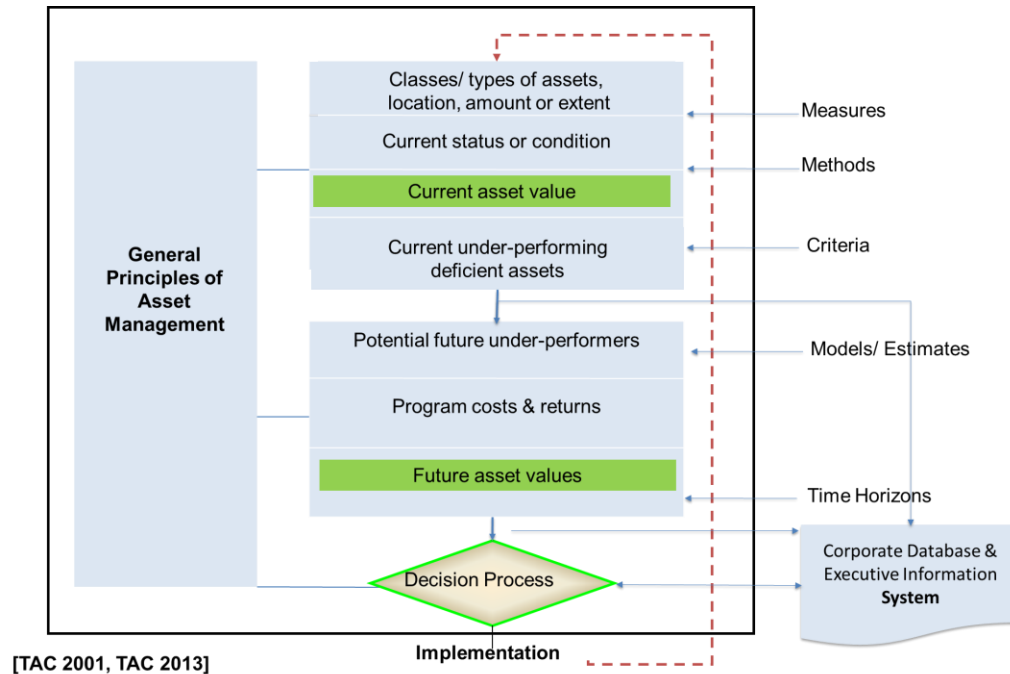
Figure 1: Overview Framework for Asset Management

Several government regulatory bodies mandate agencies to report their Capital Tangible Assets' (CTA) values within their annual statement. For example, the Canadian Public Sector Accounting Board (PSAB), the Governmental Accounting Standard Board (GASB) and the New Zealand International Financial Reporting Standards (NZ IFRS) to name a few (Alyami and Tighe 2016).

Asset valuation is an essential component of effective asset management (TAC 2013). It is an important method to demonstrate proper management of public assets and effective utilization of tax payers' money. Asset valuation is used in standard reporting, depreciation schedules, auditor requirements and condition assessments (Byrne 1994). As such, it allows agencies to demonstrate funding needs for asset preservation (Lugg 2005).

Using asset valuation financial/ accounting methods alone in reporting asset values may result in underestimating or overestimating asset values. If the underestimated asset values are used as the basis of annual fund allocation, it may result in insufficient funding to preserve assets and therefore impact the overall network performance (Cowe Falls 2004). Therefore, it is essential to integrate asset value in asset management systems to effectively manage assets while maintaining or enhancing the value of these assets (Alyami and Tighe 2016).

2   Scope and Objective

Building on previous work (Alyami and Tighe 2016), this paper introduces a methodology that integrates asset value as a performance measure in infrastructure network-level asset management decision making. To achieve this objective, an Asset Valuation Index (AVI) is developed utilizing the Multi-Attribute Utility-Theory (MUAT). A case study using data from Ministry of Transportation Ontario's (MTO) Pavement Management System (PMS2) is used to illustrate the proposed methodology.

3   Asset Valuation

Asset value holds a great promise to be incorporated in asset management as a performance measure that translates infrastructure condition in monetary terms that can be easily communicated and understood by the stakeholders (agency, policy makers, users, etc.). However, in order to effectively incorporate asset value in asset management decision making; it is imperative to understand what the value means to the stakeholders.

The accounting basis of asset valuation include: financial accounting, and management accounting (Cowe Falls et al. 2001; PSAG 2007). Asset valuation goes beyond accounting (financial reporting); it presents an engineering/ management accounting that can be used in the decision making such as evaluating various alternatives and associated benefits or liabilities.

In transportation infrastructures context, asset valuation- or asset management in general, are implemented to fixed and unfixed tangible assets within or out of the right of way (ROW) (TAC 2001, 2013). Example of fixed assets within the ROW include: pavements, bridges, signs, signals, etc. Fixed and unfixed assets out of the ROW include: maintenance depots (Ex. salt sheds, fuel tanks, etc.), material stockpiles, laboratories, communication equipment, computer hardware, etc. In addition, Haas and Raymond identified other non-tangible assets such as intellectual property, land, etc. (Haas and Raymond 1999).

There are various valuation methods that can be utilized to estimate infrastructure assets' values such as book value (BV), replacement cost (RC), and written down replacement cost (WDRC). Table 1 present example of asset valuation methods and basic definitions. It is recognized that there is no universally accepted method by the international community. It is however noted that the book value and the replacement cost methods are commonly used in highway infrastructure valuation (OECD 2001).

Table 1: Asset Valuation methods and Basic Definition (Adapted from (Amekudzi et al. 2002; TAC 2001)

Asset Valuation Method	Overview
Book Value	Present value based on historical costs depreciated to the present (commonly used for financial accounting purposes)
Replacement Cost	Present value based on cost of replacing/rebuilding the asset
Written Down Replacement Costs	Present value based on current replacement cost depreciated to asset current condition (commonly used for management accounting purposes)
Equivalent Present Worth in Place	The worth "as is". The book Value adjusted for inflation, depreciation, depletion and wear; i.e., the (accounts for changes in prices and usage; applicable to comparing with other investments)
Productivity Realized Value	The value in use. Net present value of benefit stream for remaining service life (provides a reflection of relative importance of the asset)
Market Value	Price buyer is willing to pay
Net Salvage Value	Cost to replace the facility less the cost of returning it to 'new condition' Cost of materials
Salvage Value	Present worth of the amount obtainable from disposing or recycling Facility
Option Value	Value of asset in specific circumstances (Used by private sector)

4   Proposed Framework

As shown in Figure 1, a comprehensive asset management system has the capability of identifying current network condition and needs, and to develop efficient programs taking into account future performance and value while achieving the overall objectives and policies of the agency.

Integrating asset value as a performance measure in asset management decision making introduces the need to deploy a Multi-Criteria-Decision Making (MCDM) method that incorporate the various performance measures. The performance measures are of different measurement units; for example, Pavement Condition Index (PCI), Annual Average Daily Traffic (AADT), etc. The Multi-Attribute-Utility-Theory (MAUT) is a great candidate that can unify the units through the use of the utility functions. An overview of the proposed framework that utilizes MAUT method to develop the proposed AVI is presented in Figure 2. The various components of the framework are discussed and illustrated through a case study.
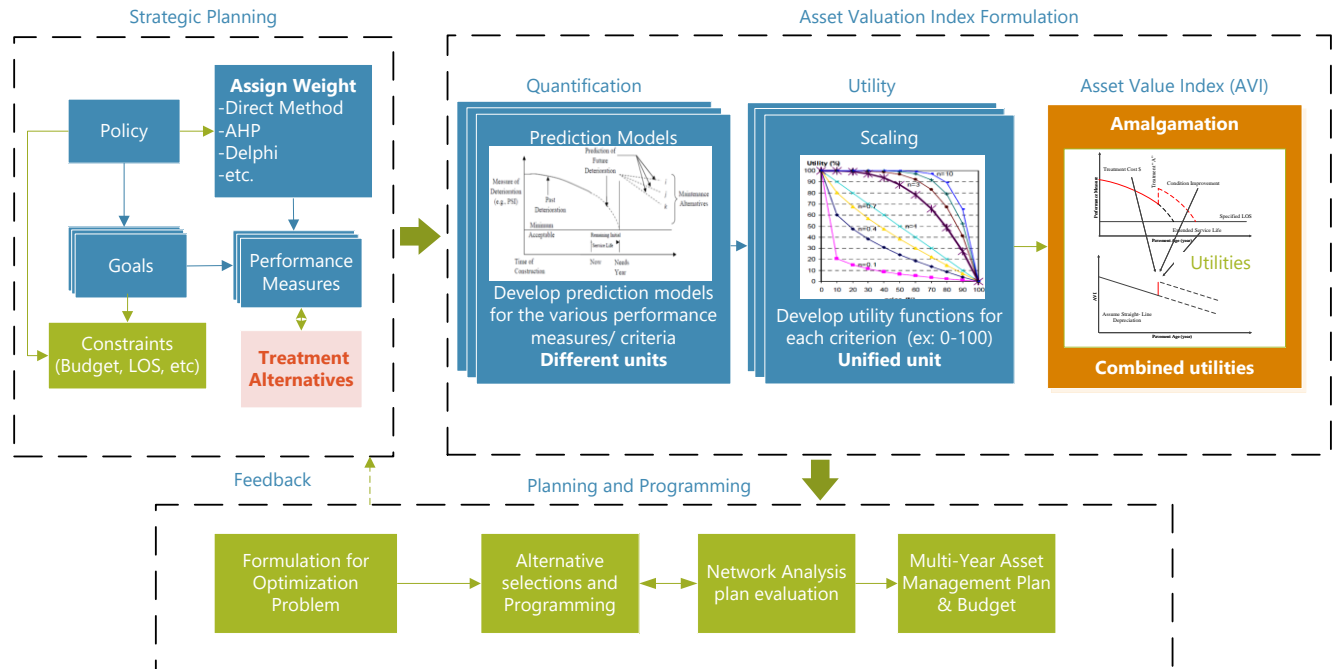
Figure 2: Proposed Value Based Asset Management Framework

5   Framework Implementation – Case Study

To illustrate the framework, a case study of a sample network from MTO's PMS2 is presented. MTO's PMS2 obtained for this study contains data collected from 1990 to 2010. The database includes 870 sections with data classified as historical data and survey data. Historical data include climatic zone (Northern and Southern); equivalent thickness; subgrade soil type; and pavement type, as well as the maintenance and rehabilitation activities applied throughout the pavement life cycle. Survey data include annual average daily traffic; truck percentage; Equivalent Single-Axle Load (ESAL); roughness (IRI m/km); rutting (cm); pavement condition index (PCI); and distress manifestation index (DMI) (Alyami and Tighe 2013; Hamdi et al. 2012). Table 2 shows a sample of the PMS2 data used in this study. The random sample network used for this study consists of 100 pavement sections, of which 29% Freeway, 42% Arterial, 29% Collectors.

Table 2 : Sample Data from MTO- PMS2

SEC	Func	KM start	KM end	Year	Rehab	AGE	PCI	DMI	AADT	Type	Thick	ESAL	Grade	enviro-	year r/m
1	FWY	0.23	4.658	2009	1996	13	69	7.38	20442	AC	101	378283	Sandy si	SO	Mil+Ovly2F
1	FWY	0.23	4.658	2008	1996	12	68	7.38	20442	AC	101	317097	Sandy si	SO	Mil+Ovly2F
1	FWY	0.23	4.658	2007	1996	11	72	7.64	20442	AC	101	317097	Sandy si	SO	Mil+Ovly2F
1	FWY	0.23	4.658	2006	1996	10	76	8.11	20442	AC	101	317097	Sandy si	SO	Mil+Ovly2F
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
9	FWY	56.66	72.94	2004	2009	8	84	8.76	90318	AC	307	1065447	Sandy si	SO	Recon AC5F
9	FWY	56.66	72.94	2003	2009	7	89	9.31	90318	AC	307	1065447	Sandy si	SO	Recon AC5F
9	FWY	56.66	72.94	2002	2009	6	91	9.45	90318	AC	307	1065447	Sandy si	SO	Recon AC5F

Note: func = Function Class, Sec# =Section Number, year= year of data collection, ESALS= Equivelant Single Axel Load, year r/m= year of application of maintenance or rehabilitation activity, pave type= Pavement Type, enviro= Environmental Zone, thick= Surface Thickness

5.1   Performance Measures

Performance measurements represents a very important underpinning of successful application of asset management (Cambridge Systematics et al. 2006). Effective asset management requires performance measures that are objectively based, consistent, quantifiable and sensitive to changes in technology or policy. Moreover, they should incorporate institutional, economic, environmental, safety, technical and functional considerations, as well as user expectations (TAC 2013). Asset management decision making is guided by its performance measures and the associated targets or thresholds. Therefore, it is important that the required performance measures and the associated LOS to be achieved are properly identified.

In order to integrate asset value as a performance measure in infrastructure asset management, the following challenges are to be considered: 1) The asset valuation method selected should be readily and easily calculated. 2) The valuation method directly relates to the asset condition, reflecting the needs and returns on investments for assets' preservation. 3) Addresses the challenges in predicting future asset values due to the instability of economic forces and the difficulty to predict future unit prices. In other words, due to the change in unit prices due to market forces, asset values may increase or decrease regardless of any asset management stewardship.

In Ontario, MTO tracks its current asset value relative to the Replacement Cost (RC) and Written Replacement Cost (WDRC) as a means of high-level asset preservation measure that is used to support the case of preservation investments (Cambridge Systematics et al. 2006). Therefore, to address the challenges above, the Asset Value Gain/Loss is introduced as a ratio of the depreciated asset value to that of a new value, expressed as follows:

[1]   Asset Value Gain/Loss (AV$_{G/L}$) = $\dfrac{WDRC}{RC}$

Where; AV$_{G/L}$ is the Asset Value (Gain/Loss) ratio, WDRC is Written Down Replacement Cost, and RC is the Replacement Cost

The ratio indicates the total asset replacement cost considering its current condition to that of a new asset. In other words, the ratio indicates the loss of value due to the asset deterioration. If a preservation or rehabilitation is applied, the WDRC value increases as the condition improves and therefore increasing the ratio, i.e. the gain in value. The ratio allows for predicting future values while addressing the challenges associated with economical fluctuations of unit costs.

Moreover, "value does not exist in the abstract and must be addressed within the context of time, place, potential owners and potential users" (Smith and Parr 1989). Therefore, one key performance indicator when considering value of an asset within the asset management framework is utilization. For example, two identical pavement sections with the same pavement condition while one has a lower Annual Average Daily Traffic (AADT) and a higher Equivalent Single Axle Loads (ESALs), maybe of the same asset value to the decision maker from an accounting prospective. Therefore, the value of a road is in the economic and social value it provides to the stakeholders whether it is in transport of goods or society commute and movement. Consequently, the asset function and utilization, heavy and passenger traffic, are included as performance criteria in the proposed methodology. This allows the decision maker to incorporate the impact of a road condition and return of investment to the users within the network.

Furthermore, in order to capture the return on investment of applying a maintenance or a rehabilitation treatment, it is imperative to measure the value-add realized over time, in addition to the immediate condition improvement. Various treatments may results in similar immediate improvements; however, the deterioration rate over time may differ. Therefore, the Remaining Service Life (RSL) is considered as a performance measure to evaluate the trade-off in investments between maintenance and rehabilitation alternatives and the impact overtime on the network preservation. In summary, the performance measures used for the proposed value-based asset management approach to develop the proposed AVI are summarized in Table 2.

Table 3: Value-Based Asset Management Performance Measures

Objective	Criterion
Improve the system overall condition and service life	Pavement Condition Index (PCI) , Remaining Service Life (RSL)
Improve Asset Value	Asset Value Loss or Gain $AV_{G/L}$
System Function and Utilization	Traffic (Passenger Cars: AADT, Track Traffic: ESALs) , Road Function

5.2   Performance Measures Weighting

The weight assigned (from 100%) to each criterion represents the importance of criteria to the decision maker. There are various methods that can be implemented to establish the weights for the performance measures, from direct weighting to more complex methods such as the Analytical Hierarchy Process (AHP). In MCDM, the method used and the change in weights can dramatically change the outcome (Bai et al. 2008). Therefore, it is imperative to review the agencies' policies and objectives to establish the weights. Sensitivity analysis of assigned weights is a key to evaluate the impact on the outcome of the MCDM.

5.3   Prediction Modelling

To evaluate feasible maintenance and rehabilitation alternatives and the impact on performance, performance modeling is needed. Performance prediction modeling is crucial in the development of asset management multi-year plans for the preservation and rehabilitation of assets. Prediction models allows for the long-term optimization of available maintenance funds as they allow to identify and predict current and future conditions based on the various decision variables and criteria. Various prediction modeling methods are available for the performance measures identified, Table 1. It is crucial to identify and use the appropriate prediction model, given the data available, to evaluate and develop accurate asset management plans. Figure 3 illustrates how performance modeling is used to predict future deterioration of pavement, expected improvements due to the application of maintenance or rehabilitation activity and determining the "need year" of application (FHWA 2002).
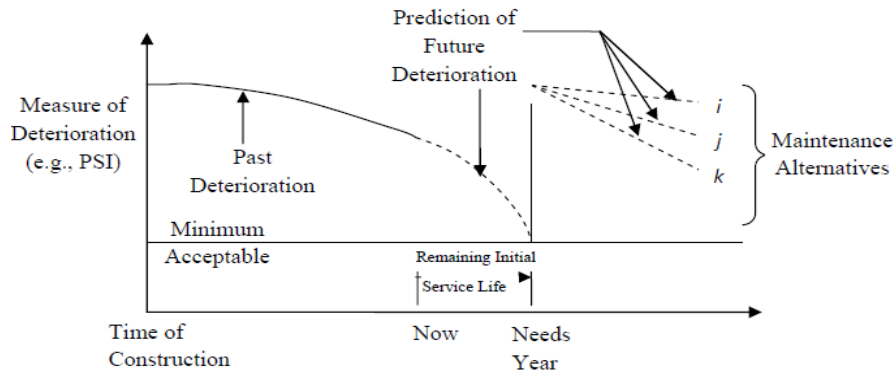

Figure 3: Deterioration Modeling and Impact of Maintenance or Rehabilitation on Pavement Performance (FHWA 2002)

5.4   Utility Functions: Scaling and Amalgamation

Performance measures are of different units (EX. PCI, Dollars, AADT, etc.). Scaling provides a common scale of measurement (say 0-1) that converts the performance measure values to a unified scale called utility. Scaling (normalizing) of all possible outcomes for each performance measure is performed separately. Scaling techniques can be classified as non-preference-based methods, and preference-based methods (Labi 2014). Non-preference-based methods include rudimentary techniques, linear scaling, and monetization, while preference-based methods include direct rating method (Labi 2014).

The procedure followed in developing the utility functions for the proposed AVI is to incorporate the thresholds or minimum level of services to evaluate the utility of the section for corresponding performance measure. For example, MTO performance targets, Table 3, were utilized to develop the utility functions for corresponding to pavement condition and value. For example, a Freeway pavement section with a PCI lower than 75, is given a utility value of zero.

Table 4: MTO PCI Performance Targets (Adopted from (MTO 2013))

Road Function	Good		Fair		Poor	
	%	PCI	%	PCI	%	PCI
Freeway	70	75	30	74-66	0	65
Arterial	65	75	30	64-56	5	55
Collector	65	70	30	64-51	5	50

The utility values for a given section are calculated for each criterion and then amalgamated to calculate the total AVI for the section. The weighted sum method (WSM), commonly used by decision makers (Bai et al. 2008), is used. The final AVI value for a given section can be calculated as follows (Bai et al. 2008; Triantaphyllou 2000):

[2] $AVI_{ij} = \sum_{j=1}^{n} W_i \ U_{ij} \ , \quad j = 1, 2, 3, \ldots, m$

Where;

W_i = Is the weight for performance measure i

U_{ij} = is pavement section j utility value for criterion i , includes:

$AV_{G/L}$ Utility value (Condition incorporated through the WDRC) for section j

AADT Utility value for section j

ESALS Utility Value for section j

Road Function Utility Value for section j

RSL Utility Value for section j

n = number of performance measures; m = number of pavement sections

5.5   Priority Programming: Formulation and Application

Since the performance measures and associated thresholds and level of services are incorporated when scaling the performance measures' utility values, the threshold for the proposed AVI is zero. The objective of the priority programming or optimization is to maximize the network AVI, subject to the available yearly budget, and performance targets over a 20 years analysis period.

In order to evaluate the outcome of the optimization using the AVI, a Do Nothing case is established. This allows to see how the network overall condition, AVI, and $AV_{G/L}$ deteriorates if no maintenance or rehabilitation is considered over the analysis period, Figure 4.
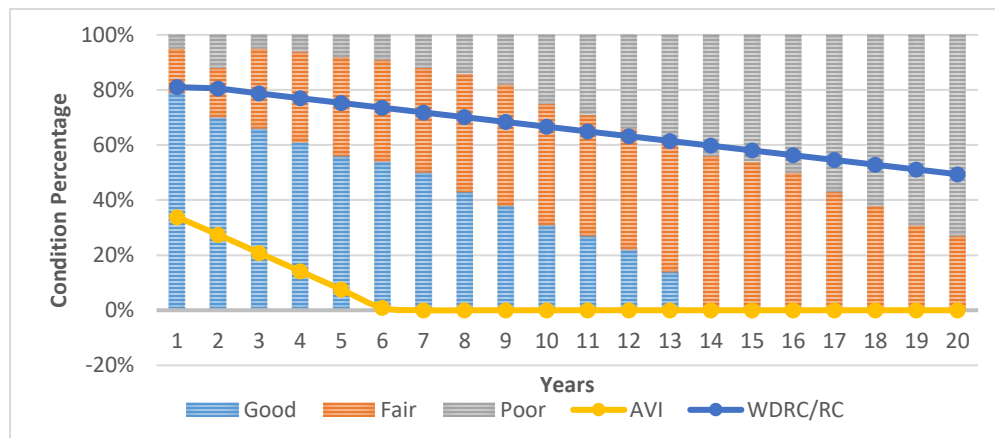

Figure 4 : Network Overall Condition Distribution- Do Nothing Option

To demonstrate the proposed AVI implementation in asset management decision making, an optimization model is developed with the aid of Excel. All inputs and calculations presented in this paper are formulated in the Excel cells. To assist with the optimization process, Evolver software is used. Evolver is a Genetic Algorithm (GA) optimization add-in for Microsoft Excel (see palisade.com/Evolver). An illustrative screenshot of the developed excel worksheet and the use of Evolver is shown in Figure 5.
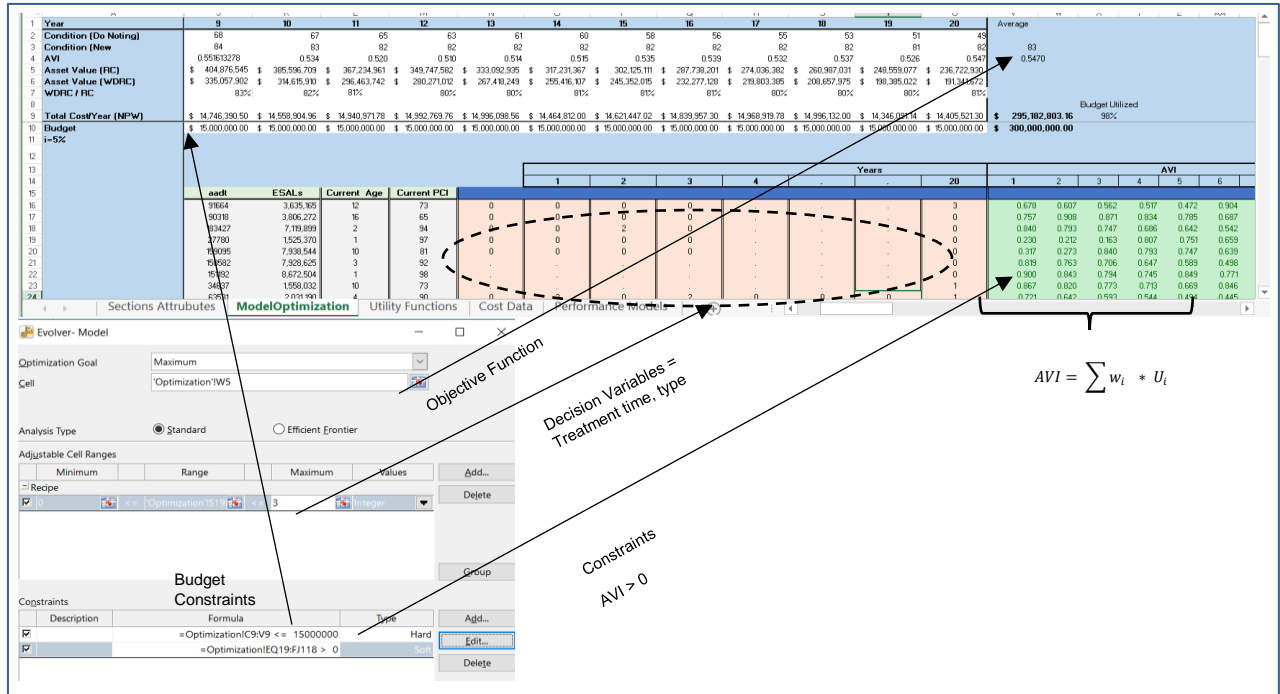

Figure 5: Model Formulation and Evolver Optimization Overview

As presented in Figure 5, the model definition box showing on the left corner allows for identifying the variables and the constraints to reach the specified objective function. The objective function shown is to maximize the total network AVI by changing the maintenance and rehabilitation activities applied at a given year while maintaining the performance measures constraints and budget. The outcome of the optimization for the network condition, $AV_{G/L}$ and AVI are presented in Figure 6 and Figure 7, respectively.
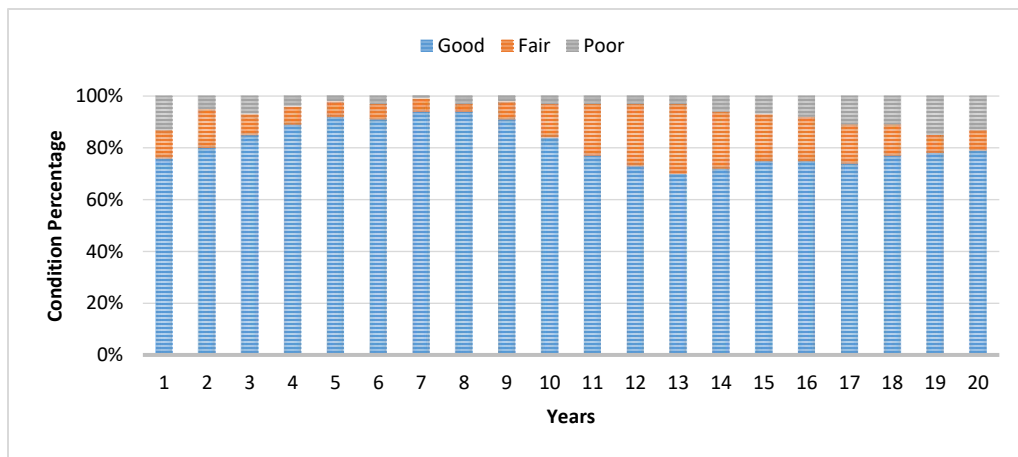

Figure 6: Network PCI Distribution- AVI Optimization Results
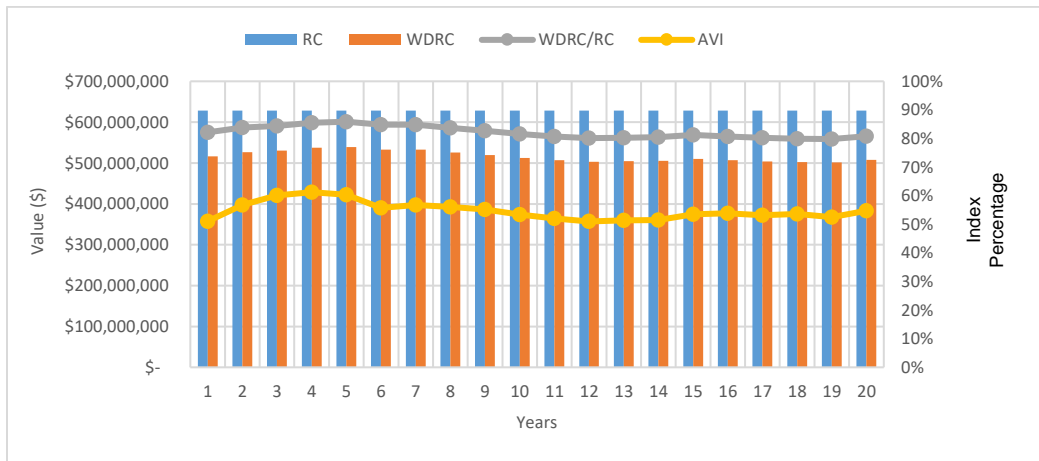
Figure 7: Asset Value Output Overview

As shown in Figure 6, the overall network condition is maintained at good condition 80% on average over the analysis period while less than 10% overall in poor condition given the budget constraint. Using the AVI index allowed for prioritization of pavement sections based on the performance measures including traffic, road function, condition, RSL and asset value.

As presented in Figure 7, the AVI average for the network is maintained above 50% in average, which indicates that it satisfies the performance measures thresholds. Using the AVI allowed for preservation of the asset value with an overall 80 % $AV_{G/L}$, i.e. WDRC to RC ratio. It is worth noting that the ratio presents a great advantage for decision makers and for justification of funding and budgetary decisions.

6   Summary and Conclusions

Asset valuation is an essential component of effective asset management and an important method to demonstrate proper management of public assets and effective utilization of tax payers' money. Asset valuation allows agencies to demonstrate value of funds needed to preserve its assets. An integration method of asset valuation in asset management is imperative to manage assets in the most optimized cost-effective ways while maintaining or enhancing the value of these assets. Asset value holds a great promise to be incorporated in asset management as a performance measure that translates infrastructure condition in monetary terms that can be easily communicated and understood by the stakeholders (Agency, policy makers, users, etc.).

This paper presented an asset valuation index, developed using MUAT method that incorporates asset value as a performance measure along with condition, road function, asset utilization and remaining service life. The paper also introduced the asset value loss/gain concept that address challenges when using current asset valuation methods, in particular for future prediction analysis. A case study using MTO PMS2 data was utilized to demonstrate the proposed index.

Integrating asset valuation in asset management as a performance measure strengths the overall asset management framework. It allows an optimized and cost-effective management of assets while maintaining or improving asset values. Moreover, incorporating asset valuation in asset management will result in more comprehensive and effective reporting and accounting of assets. That is, integrating financial/ accounting reporting and engineering reporting of assets result in a more efficient and effective capital planning and budget allocation. The proposed AVI allows for prioritization and management of assets considering various performance measures and associated level of service. Therefore, the results of this study show that the proposed index can provide an effective tool for asset management decision making.

References

Alyami, Z., and Tighe, S. (2016). "A Methodology for Integrating Asset Valuation in Transportation Asset Management." *Resilient Infrastructure, Canadian Society for Civil Engineering (CSCE)*, London,

Ontario.

Alyami, Z., and Tighe, S. L. (2013). "Development of Maintenance and Rehabilitation Program." *Transportation Research Record: Journal of the Transportation Research Board*, Trans Res Board, 2361.

Amekudzi, A., Herabat, P., Wang, S., and Lancaster, C. (2002). "Multipurpose Asset Valuation for Civil Infrastructure: Aligning Valuation Approaches with Asset Management Objectives and Stakeholder Interests." *Transportation Research Record*, 1812(1), 211–218.

Bai, Q., Labi, S., and Li, Z. (2008). *Trade-off Analysis Methodology for Asset Management*. Indiana.

Byrne, R. (1994). "Asset valuations." *2nd Annual Conference, Institute of Municipal Engineering Australia, Queensland Division (IMEAQ)*, Townsville, Queensland, Australia.

Cambridge Systematics, I., PB Consult, I., and Institute, T. T. (2006). *NCHRP 551: Performance Measures and Targets for Transportation Asset Management. NCHRP Report*.

Canada, T. (2012). *Transportation in Canada 2011 Comprehensive Review*. (T. Canada, ed.), Transport Canada, Ottawa.

Canadainfrastructure. (2016). "Canadian Infrastructure Report Card: Informing the Future." 1–164.

Cowe Falls, L. (2004). "Analysis of Asset Valuation Methods for Civil Infrastructure." University of Waterloo, Ontario, Canada.

Cowe Falls, L., Haas, R., and Hosang, J. (2001). "Asset valuation as a key element of pavement management." *Fifth International Conference on Managing Pavements*, Seattle, Washington.

FHWA. (1999). *Asset Management Primer*. Washington DC.

FHWA. (2002). *Analysis of PMS Data for Engineering Applications-Reference Manual*. Federal Highway Administration, Washington, D.C.

Haas, R., and Raymond, C. (1999). "Long Term Performance Specified Contract Framework for Road Netwroks." *Transpotation Asscoiation of Canada Annual Conference*, St. John.

Hamdi, A. S., Alyami, Z., Zhou, T., and Tighe, S. (2012). "Improving Ontario Pavement Management through Long Term Monitoring." *Proceedings of Transportation Research Board–Poster Session, Washington DC, USA*.

Labi, S. (2014). *Introduction to Civil Engineering Systems*. Wiley, Hoboken, New Jersey.

Lugg, M. (2005). *Guidance Document for Highway Infrastructure Asset Valuation*. The Stationery Office, London UK.

MTO. (2013). *Pavement Design and Rehabilitation Manual. Materials Engineering and Research Office, Ministry of Transportation, Ontario*.

OECD. (2001). *Asset Management for the Roads Sector*. OECD Publications Service, Paris, France.

PSAG. (2007). *Guide to Accounting for and Reporting Tangible Capital Assets: Guidance for Local Governments and Local Government Entities that Apply the Public Sector Handbook*. Public Sector Accounting Group, Canadian Institute of Chartered Accountants, Toronto, Canada.

Smith, G. V, and Parr, R. L. (1989). *Valuation of Intellectual Property and Intangible Assets*. Wiley, New York.

TAC. (1997). *Pavement Design and Management Guide*. Transportation Association of Canada, Canada.

TAC. (2001). *Measuring and Reporting Highway Asset Value, Condition and Performance*. Transportation Association of Canada, Ottawa.

TAC. (2013). *Pavement Asset Design and Management Guide*. Transportation Association Canada (TAC), Ottawa, Canada.

Triantaphyllou, E. (2000). *Multi-criteria Decision Making Methods: A Comparative Study*. Applied Optimization, Springer US, Boston, MA.