Development of Cross-Asset Comparative LOS Condition Index

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ABSTRACT

Comparing Level of Service (LOS) across infrastructure asset classes is difficult because of a lack of a common asset condition indicator. Some expert practitioners have suggested various types of asset value index as a common measure for comparing asset health but such an index, on its own, might mask the underlying level of service. In addition, quantifying risk and reliability is becoming ever more important when managing infrastructure assets.

Asset Condition Indices are often composites of several measured or estimated asset attributes. Pavement Condition Indices, for example, are often derived by deducting values representing many different pavement distresses from a perfect score. However, when a composite index is used, the underlying nature of the severity of distress or its extent is not evident directly from the index. One must refer to the underlying individual distress data to determine why the index got its ultimate value.

The magnitude of the deduct values are often somewhat subjective based on expert judgement relating to the relative severity of a given distress. In pavement, for instance, alligator cracking is seen to be more costly to repair than transverse cracking and is therefore given a larger deduct value resulting in a lower condition index. Although this may be reasonable for pavements, any mathematics behind the quantitative relationships between deduct values is not well documented in the literature. Quantifiable damage indices for pavements such as those used in the Highway Development and Management (HDM) framework have been in widespread use outside of North America and with the introduction of Mechanistic-Empirical Pavement Design Guide (MEPDG), are now gradually being adopted in North America providing a more consistently defined structure for quantifying pavement distress.

This paper briefly discusses the evolution of the classes of pavement indices from the traditional composite class indices through to damage indices and into those developed or now being developed to manage some other infrastructure classes including Infrastructure Value Indices.

The paper then puts forward a framework for incorporating risk and reliability with asset value indices in such a manner that both of these performance indicators could be compared across asset classes. Finally the paper describes a recently developed, damage based, LOS Index that can readily be applied to virtually any infrastructure asset class and that conveys not only the condition of the asset but allows Asset Managers to gauge the severity and density of distress through a single index number. The index can be readily implemented at any level of agency experience and requires no sophisticated data collection technology. The paper demonstrates the application of the technique through a municipal transportation infrastructure example.

Introduction

With a growing demand for management of varied assets across an enterprise, there is a need for an equitable method to compare the relative LOS on an equivalent basis. Asset classes are very different and the Key Performance Indicators (KPI) used to measure LOS are therefore also very different. A pavement's LOS is often judged by smoothness, while a water supply system might be judged by water quality and distribution reliability.

An obvious choice for a common performance indicator is an asset value indicator; a ratio of current asset value to replacement value. However in order to be useful for managing assets, the indicator must be able to be used to express not only current but future performance. An excellent treatise on the use of an asset valuation indicator for asset management was advanced in 2005[i] . Readers are urged to review that document as background.

Since then however, the concept of risk, combining likelihood and consequences, as another indicator of asset[ii] performance has gained increasing acceptance. This paper proposes a framework whereby the different Key

Performance Indicators (KPI) for various asset classes could be passed through what might be termed a “universal translator” to arrive at single comparative Asset Condition Indicator (ACI) that represents an asset’s LOS, condition depreciated value, reliability and level of risk.

This paper first describes some of the types of performance indicators that have been developed and the perceived benefit or advantages of each type is outlined. The paper goes on to describe a framework for the proposed multi-purpose rating and follows up with an example application using municipal curb/gutter and sidewalk assets.

Types of Performance Indicators

The following is not intended to be an exhaustive list of types of performance indicators, but rather to illustrate the benefits or strong points of the different types in order to highlight what attributes a multi-purpose rating would, ideally, possess. The indicators demonstrate an evolution of thinking regarding, in particular, the consideration of asset value and risk and reliability.

Present Serviceability Rating

The serviceability is rated subjectively by a panel made up of people selected to represent several important groups of asset users. Rating is typically in terms of good, fair or poor or based on a numerical scale 1 – 5 or 1 - 10. An example of this methodology is the Present Serviceability Rating (PSR) developed as part of the 1950’s American Association of State Highway Officials (AASHO) road test[iii]. Another example is the Riding Comfort Index (RCI) developed in the early 1970’s[iv]. The main benefit of this type of rating is it reflects the level of service as perceived by users. Predicting future serviceability would need to be based on historical ratings used to develop empirical models.

Present Serviceability Index

The Serviceability Index measures physical Key Performance Indicators (KPI) of an asset (roughness or cracking on pavements for example), and uses multiple regression analysis of the various KPI’s to derive and validate a mathematical index through which the PSR can be satisfactorily estimated from objective measurement of an asset’s KPI’s. An example of the serviceability index called the Present Serviceability Index[ii] (PSI) was also developed as part of the AASHO Road Test. The benefit of this index is it removes the subjectivity of a rating panel. If the KPI’s used to derive the index can be modeled, the future PSI can be predicted. Alternatively the PSI could be directly predicted empirically from historical data.

Condition Index

One widely used index is the US Army Corps of Engineers (USACE) Pavement Condition Index[v] (PCI). An American Society for Testing Materials (ASTM) standard, defined by ASTM D5340 for Airport Pavements and ASTM D6433 for Roadway Pavements. Developed by the United States Army Corps of Engineers in the late seventies, it uses a statistical sampling technique to rate the condition based on visible distresses. “The distresses differ in type, severity and extent. Because of the large number of conditions possible, producing one index that would take into account all three factors was a considerable problem”, overcome by the introduction of the concept of “Deduct Values”, derived from expert opinion [Shahin]. Using a somewhat complex iterative process, the deduct values for each distress, severity and extent are subtracted from a perfect score of 100 to arrive at a composite distress index. Another example of a composite distress index is the Surface Distress Index[vi] (SDI) also called a Visual Distress Index or Visual Condition Index.

These condition indices result in a repeatable measure calibrated to expert opinion and has the additional benefit in that the entire asset’s surface need not be evaluated. The PCI is measured using a sampling technique whereby only a statistically significant number of “sample units” of an asset’s surface need be measured to arrive at a repeatable measure for the whole asset. As with the PSI, if the KPI's used to derive the index can be modeled, the future PSI can be predicted. Similar to PSI, PCI can be directly predicted empirically from historical data.

Structural Adequacy

If assets are newer and/or have no visible distress they can be assessed for robustness by comparing the load carrying capacity to the demand load for structures, in terms of the capacity/demand ratio. An example of this index type applicable to pavements is the Structural Adequacy Index (SAI) [TAC 1997]. This index is intended to evaluate the current adequacy of a pavement structure relative to its ability to withstand expected traffic loadings. When appropriately used these types of indices provide a forecast of remaining life of an asset, as well quantification of current and future reliability.

Composite Quality Index

A short coming of the PCI is that it does not directly consider the users experience (perceived LOS), as do the PSR/PSI and the RCI. None of these indices provide an indication of future reliability like the SAI. These short comings lead to the development of a composite indicator called the Pavement Quality Index (PQI) [TAC 1997]. For this index, the panel rated riding comfort is converted to an index (RCI) and combined with a PCI/SDI and an SAI. Each of the three component indices is weighted based on asset owner's perception of importance. Ride might not be as important on lower speed municipal roads versus high speed highways for example. Each of the indices comprising the composite index might in themselves be an aggregation of other measurements. Each level of aggregation leads to loss of information. Also, because of the adjustable weighting factors, the PQI is not standardized between agencies.

The concept of including perceived level of service and reliability as well as condition in an overall index is an important benefit. It leads to the concept that a multi-purpose asset condition indicator might be derived from either a single or multiple input information sources. It is the resultant asset condition indicator that should be common across asset classes, not the inputs.

Asset Valuation Index (AVI)

The current value of an asset is often expressed in terms of its replacement cost depreciated to current condition of the asset called its Written Down Replacement Cost[vii] (WDRC). For comparisons between values of a portfolio of assets the WDRC is converted to an index. In the context of facilities such as buildings it is called the Facility Condition Index. The Facility Condition Index[viii] (FCI) is a standard facility management benchmark that is used to objectively assess the current and projected condition of a building asset. By definition, the FCI is defined as the ratio of current year required renewal cost to current building replacement value. Building condition is often defined in terms of the FCI as follows:(Good) 0 to 5 percent FCI,(Fair) 5 to 10 percent FCI (Poor) 10 to 30 percent FCI, (Critical) greater than 30 percent FCI. The purpose of the FCI is to provide a means for objective comparison of facility or building condition as well as allowing senior decision makers to understand building renewal funding needs and comparisons.

Another indicator of asset value is Transport Canada's Net Salvage Value (NSV) [Cowe Falls et al 2005]. Transport Canada has suggested that NSV, which is the difference between the rehabilitation costs and the replacement cost, is a method appropriate for railways.

Quantifiable damage indices (such as the Transportation Research Board's (TRB) Mechanistic Empirical Pavement Design Guide's (MEPDG) top-down fatigue cracking, bottom up fatigue cracking, rut, roughness and pavement strength or the Highway Development and Management's (HDM-4)[ix] All structural Cracking (ACA), Wide Structural Cracking (ACW), rut, roughness and Modified Structural Number (SNP)) are based on either structured-empirical models or mechanistic-empirical models and are therefore, by definition predictable, so can be used directly to calculate future repair and rehabilitation cost. The damage indices also provide a firm basis for Life-Cycle Cost Analysis (LCCA) in that different rehabilitation intervention triggering levels can be explored to obtain an optimal Life Cycle Cost.

The authors have used these damage indicators to formulate a pavement specific Net Salvage Value index called the Pavement Asset Value Index (PAVI). With this methodology, individual surface/visual distresses such as fatigue cracking, thermal cracking, rutting, roughness and measured structural weakness are assigned maintenance and repair treatments and quantities on a unit cost basis. The ratio of NSV to the replacement cost of the pavement asset expressed as a percentage produces the PAVI.

The creation of a reliable damage index, herein after referred to as an Asset Damage Index (ADI), is fundamental to the requirement for prediction of cost information into the future as is required by an LCCA but also useful in predicting the future AVI. The key concept here is that predictable damage (predicted cracking), predictable reliability (predicted SN relative to traffic forecasts), predicted LOS (predicted roughness) and predicted user safety (predicted rutting) is used to forecast the amount of maintenance and rehabilitation, and hence costs to bring the asset to as-new condition, in any year into the future. An LCCA using damage indices can be applied to any asset, a road, a bus, a BBQ, etc.

Safety Index

An example of a Safety Index is Utah State Department of Transportation's (UDOT) Safety Index[x]. The UDOT Safety Index is a value that combines multiple safety statistics into a single, zero to ten scale number. UDOT uses the Safety Index for project prioritization and roadway safety assessment. To develop the Safety Index, individual, zero to five scores are derived for four safety factors by comparing the value of an individual road segment against the statewide distribution for roadways of similar volume and functional class. The scoring breakdown is:

0 – segment with no crashes
1 – segment below the 50th percentile
2 – segment from the 51st to the 75th percentile
3 – segment from the 76th to the 90th percentile
4 – segment from the 91st to the 95th percentile
5 – segment above the 95th percentile.

After each factor receives a score, the scores are summed. The summation results in a zero to 20 value, which is then divided by two to create the final zero to ten Safety Index. The Safety Index brings a measure of risk to asset comparisons.

Asset Health Index

As an example of the introduction of risk, reliability and criticality a KPI advanced by Deloitte[xi] for use in the Canadian Electricity Association is the Asset Health Index (AHI) comprised of five components:

1. Asset identification
2. Condition
3. Usage
4. Failure modes
5. Criticality/risk information

There is no standard way of calculating Asset Health Indices, as each organization will place different values on the various factors involved. As a basic example, one utility[1] considers the end of life of a pole to be based on the "effective" circumference; that being determined by a combination of measured circumference, the un-compromised shell thickness and the amount of deterioration due to insect infestation (Woodpecker rating) of

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[1] The Company's identity was described as confidential in the document.

the pole. A pole's strength is expressed as a percentage in terms of its remaining effective circumference relative to the required circumference. A relationship is then developed between effective circumference and remaining life. The company plans replacement of poles with a remaining strength of 60% or less and prioritizes these projects based on risk. This is an example of combining a Capacity Demand calculation (like the SAI) with a criticality/risk information to arrive at the AHI. Interestingly, the process does not include an asset value.

Risk Matrix

The AHI was by no means the first example of including risk and reliability as an indicator of LOS. The British Columbia Auditor General for Local Governments (AGLG) identified benefits associated with a risk-based approach[ii] stating it,

> *"helps you prioritize your resources, optimize your budget, avoid unnecessary costs and achieve a higher return on your local government's investments in capital assets. By identifying and assessing the level of risk associated with each potential asset failure, you can target scarce resources to ensure vital services remain available and critical assets are appropriately inspected, monitored and covered by preventative maintenance.*
>
> *"Risk analysis is about determining the likelihood and consequence of asset failure, each rated for criticality from low to extreme. Consequences are typically classified as economic, operational, social and environmental and public health and safety. The risk rating diagram can give a good idea of the methodology used by many public sector organizations. As risk likelihood and consequence increase, the rating moves from low to extreme.*
> *It's best to carry out risk modeling before assessing asset condition. In fact, risk assessment should direct how and when you assess condition. Assets with an extreme criticality rating should receive detailed condition assessment, engineering reviews and field monitoring."*

Figure 1 shows the risk rating matrix identified by the AGLG as methodology used by many public sector organizations, for assigning a risk index in terms of low, medium, high or extreme risk. The Likelihood score multiplied by the Consequence score defines a risk index on a scale of 1 to 25.

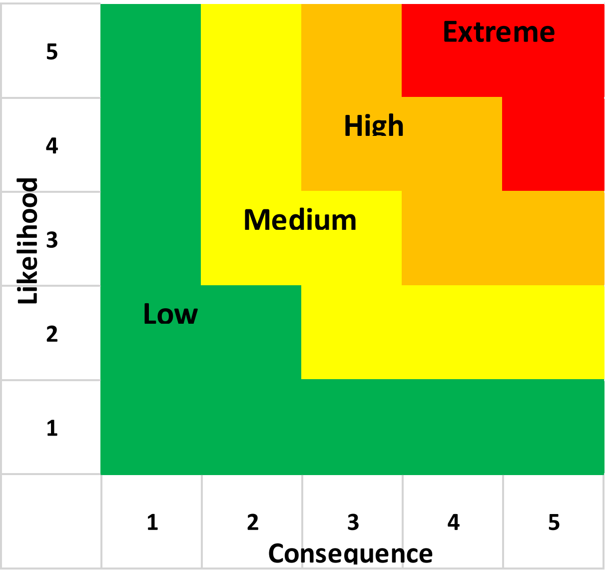


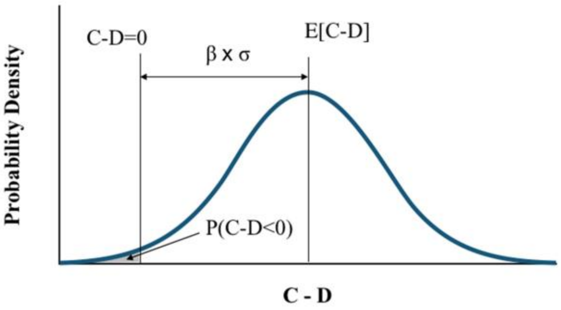
Figure 1 – BC AGLG Risk Matrix

The document does not provide a methodology for determining either the Likelihood or the Consequence although assignment of an asset's "Likelihood" score is presumably deduced from its stage within its life-cycle. The AGLG provides a simple gauge or standard for lifecycle costing as developed by the Public Sector Digest:

0-25% through the asset’s lifespan – minor maintenance
25-50% through the asset’s lifespan – major maintenance
50-75% through the asset’s lifespan – rehabilitation
75-100% through the asset’s lifespan – replacement

Reliability Index

With the reliability approach, much is left to the judgement, preferences and priorities of the individual. In 2011 the United States Army Corps of Engineering documented a Reliability Index[xii] to be used for reliability analysis of structural assets such as drainage structures and bridges. With this method, the demand D and the capacity C are the uncorrelated random variables. Both variables are represented by normal distributions with their means and standard deviations. Therefore, the safety margin C-D has a normal distribution, by which P(C-D<0) can be obtained from a closed form solution as illustrated in Figure 2, where β is the reliability index, E(C-D) is the expected (mean) value of C-D, and σ is the standard deviation. Greater values of β represent greater structural reliability or lower probability of failure.



$$\beta = E\,[C\text{-}D]\,/\,\sigma$$
$$\sigma = (\sigma_C^{\,2} + \sigma_D^{\,2})^{1/2}$$
$$\beta = E\,[C\text{-}D]\,/\,(\sigma_C^{\,2} + \sigma_D^{\,2})^{1/2}$$

Figure 2[xiii] – Reliability Index

The inverse of the Reliability Index is the Risk Index representing the Probability of Unsatisfactory Performance (Pup) which in turn quantifies, in terms of percentage, the chance or likelihood of loss of reliability. This Pup multiplied by the monetized consequences of unsatisfactory performance defines the risk [USACE 2011]. The authors have developed[xiv] methodology for the use of this technique for managing highway drainage culverts considering climate change risk. The advantage in using this approach is that so long as the consequences can be appropriately quantified [USACE 2011], it is possible to compare risk across asset classes. Since risk encompasses safety it negates the need for a separate safety index. The capacity versus demand concept combined with risk satisfies the objectives of the Asset Health Index. The risk assessment is asset independent.

Development of a Cross Asset Multi-Purpose Asset Condition Index

The authors propose of a common measure of asset status that combines many of the benefits of existing types of reporting measures, while at the same time providing a basis for compatible comparison between asset classes.

The benefits of the previously discussed, existing reporting measures are seen to be as follows:

- Provides an indication of users’ perceived level of service;
- Indicates condition relative to measurable deterioration;
- Indicates remaining life;
- Places a current value on the asset;
- Defines triggering levels for applying interventions;

- Forms the basis for cost benefit analysis;
- Defines the level of risk;
- Can be applied to any infrastructure asset.

The authors are proposing a framework for development of this type of asset status rating by combining the concept of asset valuation using a Net Salvage Value index (called an Asset Value Index) with a Reliability Index whereby the two indices are mathematically inter-related. That is, if an asset manager can determine either index the other can be mathematically computed.

The premise for this framework is that it be risk-based, and that the quantification of the consequences of unsatisfactory asset performance are determined in a consistent manner across all assets and asset classes.

The asset's reliability is defined by the probability that the asset will perform satisfactorily through to the next scheduled inspection. The key to development of the framework is establishing a relationship between an asset's reliability and its remaining value. In this proposed framework remaining value, expressed as a percentage, is defined as the cost to replace the asset minus the cost to bring the asset in its current condition back to "as-new" condition divided by the cost of asset replacement.

Current Asset Value (%) = (Asset Value – Cost to Bring Asset to As-new Condition)/Asset Value

It is proposed that Current Asset Value (%) = Asset Condition Index (ACI)

The asset's current value expressed as a percentage of the asset's current replacement cost is then related to the asset's reliability using a suitable numeric expression whereby the 0% – 100% remaining asset value range is expressed in terms of a 0% - 100% probability/reliability range. This can be done as a separate exercise for each asset class or a generic relationship such as that shown in the illustrative framework given in Figure 3 could be used directly.

In either case, once the Asset Value – Reliability relationship is established, the asset's current status can be assessed either by inspection to determine its current asset value or estimating the probability that the asset will perform satisfactorily through to its next inspection.

The inspection/asset valuation process is further simplified by providing treatment intervention triggering ranges related to maintenance, preservation, rehabilitation and replacement. In this framework the LOS is aligned with the condition ranges. The inspector defines what work needs be done, the work is assigned a cost and the ACI is calculated. The repair costs can be defined as a percentage of asset replacement value to simplify the ACI calculation.

Alternatively, the inspector might conduct a risk/reliability analysis similar to that described in the USACE document EC 1110-2-6062 "Risk and Reliability Engineering for Major Rehabilitation Studies" to determine the reliability or simply estimate the reliability based on expert knowledge.

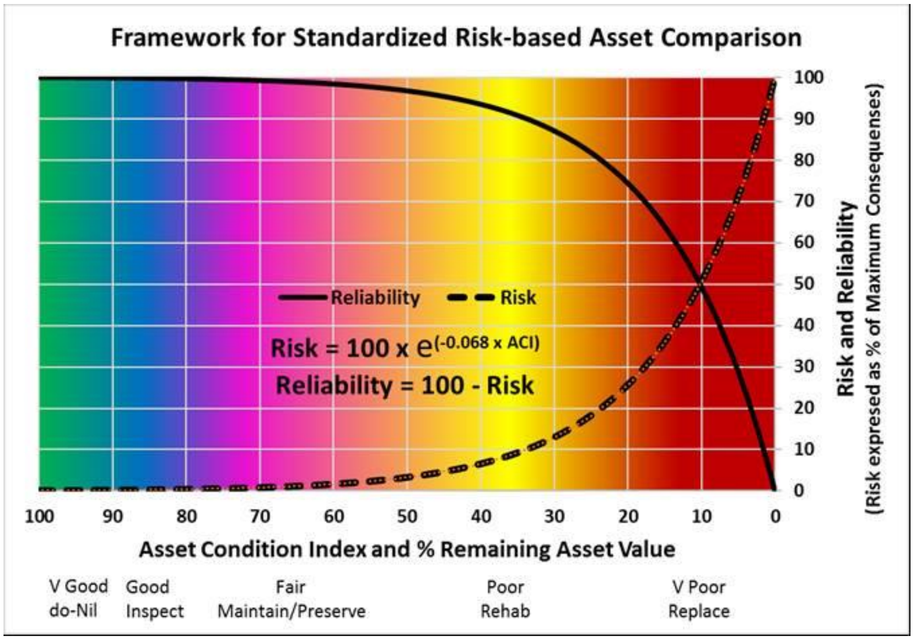


Figure 3 – Proposed Multi-Purpose Asset Condition Indicator

Once the reliability/asset value relationship has been established for a given asset class, the ACI can be determined either by direct measurement of asset condition or by first determining reliability directly from the asset's point within its life-cycle or a reliability analysis.

The concept is that no matter how an asset is currently being rated it can be translated through the proposed framework illustrated in Figure 3 into these standardized ACI/AVI and Risk and Reliability indicators.

It must be stressed that the ACI/AVI is only an indicator of the asset's condition state at a point in time it is not a predictive model in and of itself. The prediction of AVI is done through underlying asset specific damage indices or by predicting asset specific reliability by whatever measures are available and converting mathematically to ACI. Alternatively ACI might be modeled empirically directly from historical ACI values for a given asset.

Life-cycle cost Analysis is best done using the underlying damage model indices but now the future risk can be considered as a cost, (or risk reduction as a benefit), in the LCCA [Stmichel et al 2017].

Example Asset Evaluation

An example is provided using Curb/Gutter and sidewalk assets. In this example the assets are to be visually rated from digital images of the assets captured at 5 meter intervals along the length of these linear assets. An asset is defined as a **Section** which encompasses the entire length of the asset from one intersection to the next (generally block – to block) and one on either side of the street where they exist.

Sample Unit is defined as the 5m visible length, of these linear assets represented by the central portion of each digital image. However, not all images have Sample Units visible in each image. In some cases, an asset may not exist at a given location or may not be visible due to parked cars, other obstructions, or camera angle. A Sample Unit only exists, for an asset, if it is readily visible in the central portion of an image.

On each Sample Unit, several distresses are rated in each of the following severity levels, subjectively by the rater:

- **Excellent** = Asset Appears relatively New and has no visible distresses – Entire Sample Unit is assigned a deduct value of **Zero**, all other distress deduct values are set at **Zero**.
- **Good** = Asset appears relatively Old and has no visible distresses – Entire Sample Unit is assigned a deduct value of **One**, all other distress deduct values are set at **Zero**.

- **Fair** = The distress is visible but in the rater's opinion, the distress does not affect the function of the asset and no repair can, (or needs), to be done (e.g. a just visible crack). The distress is assigned a deduct value of **Two**.
- **Poor** = The distress has progressed to the point where a maintenance repair, could be readily and cost effectively applied to maintain the functionality of the asset. The distress is assigned a deduct value of Five.
- **Very Poor** = The Sample Unit has deteriorated to the point where, maintenance repairs will be insufficient to economically re-establish proper function of the asset. The Sample Unit needs to be replaced. The Sample Unit is assigned a Deduct Value of **Ten**.

A matrix of deduct values, Sample Unit level treatments and distress/damage based triggers is given in Table 1.

						Sample Unit Based					
Sample Unit Deducts							Field Inspections		Maintenance Repairs		Rehabilitation
	Severity Level Deduct Values							Sample Unit Level Triggers for Works Program Development			
Asphalt Sidewalk	**Excellent**	**Good**	**Fair**	**Poor**	**Very Poor**	**Trigger**	**Deduct = 2**	**Trigger**	**Deduct = 5**	**Trigger**	**Deduct = 10**
Cracking	0	1	2	5	10		Field Inspection (Section)		Crack fill (Sample)		Replace (Sample)
Cross Slope			2	5			Field Inspection (Section)		Shim Lift (Sample)		Replace (Sample)
Faulting			2	5			Field Inspection (Section)		Fillet (Sample)		Replace (Sample)
Ravelling			2	5			Field Inspection (Section)		Spray Patch (Sample)		Replace (Sample)
Obstruction			2	5			Field Inspection (Section)		Remove (Obstruction)		Re-align (Sample)
Ponding			2	5			Field Inspection (Section)		Shim Lift (Sample)		Replace (Sample)
Settlement			2	5			Field Inspection (Section)		Shim Lift (Sample)		Replace (Sample)
Utility Cuts			2	5			Field Inspection (Section)		Re-Patch (Sample)		Replace (Sample)
Concrete Sidewalks	**Excellent**	**Good**	**Fair**	**Poor**	**Very Poor**		**Deduct = 2**	**Trigger**	**Deduct = 5**	**Trigger**	**Deduct = 10**
Cracking	0	1	2	5	10		Field Inspection (Section)		Crack fill (Sample)		Replace (Sample)
Cross Slope			2	5			Field Inspection (Section)		Shim Lift (Sample)		Replace (Sample)
Faulting			2	5			Field Inspection (Section)		Fillet (Sample)		Replace (Sample)
Obstruction			2	5			Field Inspection (Section)		Remove (Obstruction)		Re-align (Sample)
Ponding			2	5			Field Inspection (Section)		Shim Lift (Sample)		Replace (Sample)
Settlement			2	5			Field Inspection (Section)		Shim Lift (Sample)		Replace (Sample)
Utility Cuts			2	5			Field Inspection (Section)		Re-Patch (Sample)		Replace (Sample)
Spalling			2	5			Field Inspection (Section)		Parge (Sample)		Replace (Sample)
Fillets			2	5			Field Inspection (Section)		Re-Fillet (Sample)		Replace (Sample)
Curb & Gutter	**Excellent**	**Good**	**Fair**	**Poor**	**Very Poor**		**Deduct = 2**	**Trigger**	**Deduct = 5**	**Trigger**	**Deduct = 10**
Cracking	0	1	1	5	10		Field Inspection (Section)		Crack fill (Sample)		Replace (Sample)
Faulting			1	5			Field Inspection (Section)		Shim Lift (Sample)		Replace (Sample)
Spalling			1	5			Field Inspection (Section)		Fillet (Sample)		Replace (Sample)
Joints			1	5			Field Inspection (Section)		Parge (Sample)		Replace (Sample)

Table 1 – Sample Unit Based: Distresses, Deduct Values, Trigger Values, and Treatments

Development of a Generic Asset Damage Index

The premise behind this Asset Damage Index (ADI), is that one damage definition be suitable for any asset class and that the ADI value directly informs the Asset Manager as to which Sectional Treatment Category is suggested.

Sectional Treatment Categories

The proposed treatments fall into five sectional treatment categories:

- **Do-nil** – At the section level, no action required.
- **Field Inspection** – At the Section level where distresses exist but no maintenance repairs are suggested. The field inspection validates the distress rater's judgement and provides for inspection of the entire asset including portions that were not visible from the digital images.

- **Maintenance** – Repairs to a Section where no Sample Unit replacements are suggested. Repairs are defined by distress type as recorded in poor condition by the rater. This treatment also includes a full review of the section to validate the rater's opinion and to review those portions of the asset not readily visible in the digital images.
- **Rehabilitation –** Repairs to a Section where some Sample Unit replacements are suggested by the rater. This treatment also includes a full review of the section to validate the rater's opinion and to review those portions of the asset not readily visible in the digital images.
- **Reconstruction –** Reconstruction of a Section where so many Sample Units are suggested for replacement or that so many sample units are suggested for maintenance repair, that it becomes more economical to reconstruct the entire Sectional Asset. In this case defined as either more than 30% of Sample Units within a Section require replacement or the combination of Sample Units within a Section that need repair and/or replacement exceeds 60%.

Sectional density accounts for both the extent of the distress and the extent of the asset class that was measured for this distress.

Sectional Densities = number or Sample Units containing a given deduct value/Total Number of Sample Units rated on a given asset Section. Each Sample Unit is assigned the highest Deduct Value rated, either a 0, 1, 2, 5 or 10. Total of all Deduct Densities = 100%. There are five density calculations for each section.

D_0	D_1	D_2	D_5	D_10
Density_0	Density_1	Density_2	Density_5	Density_10
% Deduct Values =0	% Deduct Values =1	% Deduct Values =2	% Deduct Values =5	% Deduct Values =10

The ADI is on a scale of 0 – 10 and is based on the lowest value of either 50 minus the D_10 density or 80 minus the D_5 density. If no D_5 or D_10 densities exist on a Section the ADI is derived from the proportion of either D_2 density or D_1 density yielding the lowest ADI. The calculation is as follows:

Asset Damage index (ADI) = IF(**D_5** + **D_10** > 0, IF(**D_10** > 0, MIN(50-**D_10**,80-**D_5**), 80 - **D_5**), IF(**D_2** > 0, 90 - **D_2**/10, 100 - **D_1**/10))/10

The ADI is set to zero if the equation results is less than zero. The ADI is also rounded to one decimal place.

In this way the resulting ADI directly informs the asset manager regarding the treatment category for the Section. The extent of the damage is also immediately evident through the damage index, an index of 5 has requires significant maintenance but no rehabilitation while an index of 7.9 requires only a very little maintenance.

Sectional Trigger Values

- **ADI > 9** No Distress ----> (Do-Nil),
- **ADI 8 - 9** Some Distress Exists ----> (Field Inspection)
- **ADI 5 - 8** Some Maintenance Repairs Suggested (Develop Maintenance Program)
- **ADI 2 - 5** Less than 30% of Sample Units need Replacement and/or greater than 30 % of Samples need Maintenance Repair ----> (Develop Rehabilitation Program)
- **ADI < 2** More than 30% of Sample Units need Replacement and/or greater than 60 % of Sample Units need Maintenance Repair ----> (Replace Asset)

Decision Trees (Triggers)

At the Sample Unit and individual distress level, by definition, the trigger levels are defined by the deduct values. A deduct value of 5 for any distress triggers its Maintenance repair. There are however further decisions to be made for the treatment of the overall Section. If no distress exists on a section, i.e., all Sample Units have Deduct values of either a Zero or a One, it would be assigned a “Do-Nil” treatment. In other words, no further action required at this time.

If there are any recorded distresses and if all recorded distresses in all Sample Units on a section have a rating of Two, there is no repair action suggested, however the Section would be assigned a “Field Inspection” treatment.

If there are any repairable distresses or suggested Sample Replacements at all on any Sample Unit within a Section, the Section is flagged for a Work Program Development process as shown in Figure 4.

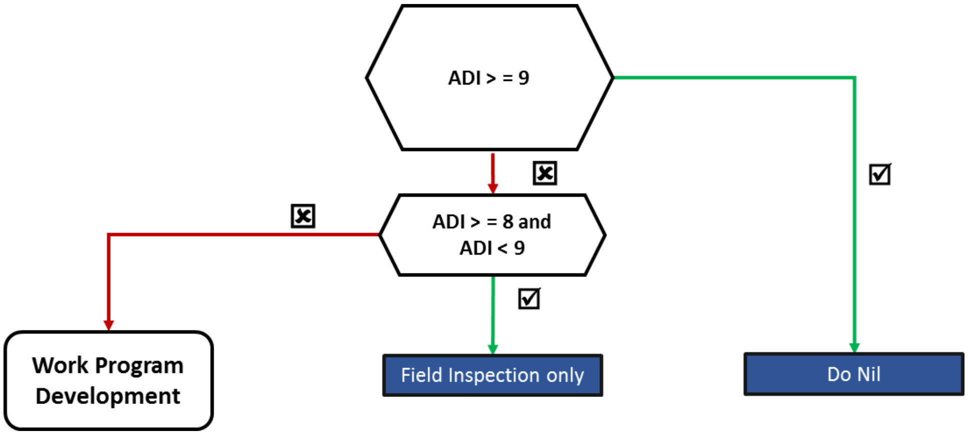


Figure 4 – Work Plan Development Decision

Once enough maintenance repair or Sample Unit replacement is required on a section it becomes more economical to replace the asset through reconstruction. It is proposed that if more than 30% of the Samples Units in a given Section require replacement or that more than 60% of the Sample Units require either replacement or some maintenance repairs, the entire Section be considered for replacement. Assets which are not candidates for full replacement are divided in to those that need partial replacement and those which require maintenance repairs only. (Figure 5)

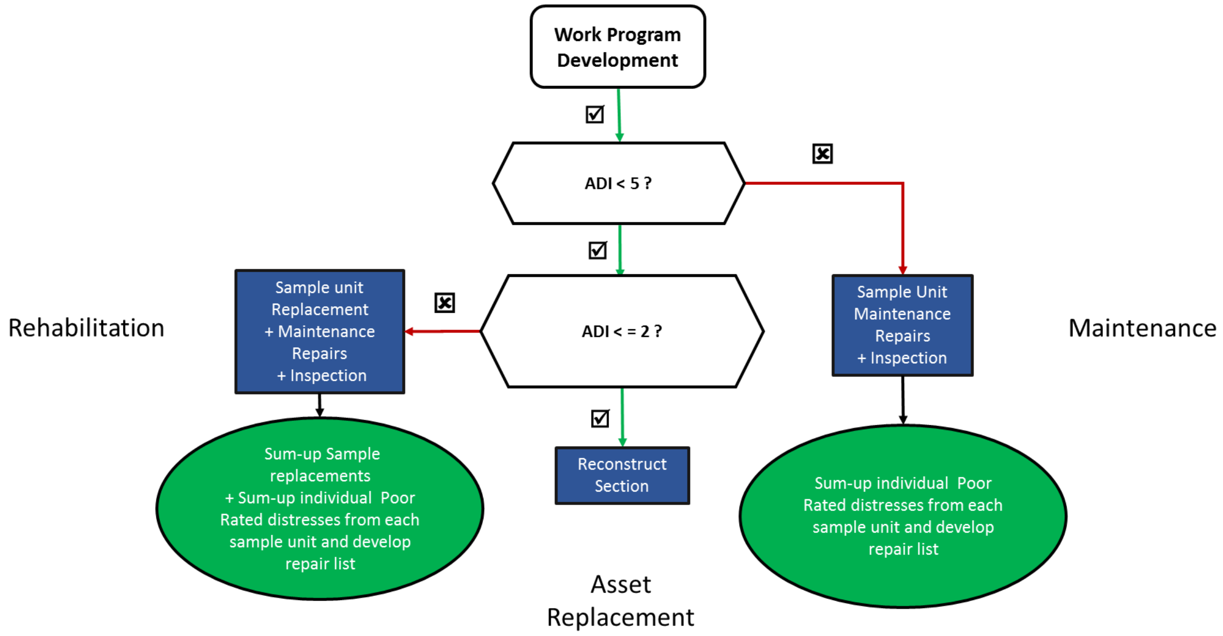


Figure 5 – Work Plan Development Process

Sample Unit Level: Quantity and Cost Development

Developing the work plan consists of deriving a count of each individual, repairable distresses from each sample unit within a Section for each asset. That count, divided by the number of the valid sample units in the Section, provides an individual distress density for each distress. The density is multiplied by 5 (five meters is the approximate length of the Sample Unit) and then divided by the asset's length. This provides a percentage of asset length in need of repair for each individual distress. A unit cost, per 5m length, for each repair type listed in Table 1 is applied to each individual Sectional distress density to arrive at cost estimates, by repair type, expressed as a percentage for each Section.

Calculating Asset Condition/Asset Value Index

By definition, an ADI of 10 has no cost to bring it to "as-new" condition. Also by definition an ADI of < than 2 has a cost equal to 100% of the replacement value of the asset therefore an AVI of 0. ADIs of between 9 and 10 need no repairs, ADIs between 8 and 9 will need varying degrees of inspection, those between 5 and 8 will increasingly intensive maintenance repairs and ADI between 2 and 5 will require increasingly intensive combinations of Sample Unit replacements and maintenance repairs. These asset costs can be calculated directly by summing density based unit costs derived above or alternatively by prorating based on judgement.

An example using judgement might be that defects that are not yet in need of maintenance should not be valued at more than 10% of an asset's value and maintenance should not be more than 30% of its value prior to initiating a rehabilitation. Prorating costs between 100% and 30% (ADI from 2 to 5) for increasingly expensive rehabilitation, 30% and 3% (ADI from 5 – 8) for increasingly expensive maintenance and between 3% and 0% for increasingly expensive inspections. These costs subtracted from 100 give the AVI/ACI value.

Conclusions

An asset value index based on net salvage value enables cross asset comparison of tangible capital assets. The combination of damage indices to assess repair costs as used to derive a Net Salvage Value based Asset Value Index makes provides a cross asset performance indicator possible.

If the Asset Damage Index is constructed in such a way as to readily define overall condition state in terms of repair requirements, it will make the ADI directly useful for assessing Asset condition because very little of the underlying condition information is lost in the conversion from damage measurements to damage indices and consequently to value index.

If it can be agreed that LOS is defined by perceived condition and reliability, then both are required to define it. The two could be measured and tracked independently, or a mathematical relationship developed such that one index and an associated equation is developed for each asset class.

This framework is intended to spark some discussion around these concepts. The example damage index and framework provided by the authors, is believed to be a reasonable starting point for developing a multi-purpose asset comparison indicator, and the beginning of a replicable and defensible approach to comparing apples and bananas.

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