VDOT

Virginia Department of Transportation

SPECIAL STRUCTURES HEALTH INDEX EXPERT ELICITATION FOR TUNNELS

Marc Stecker, PE, & Adam Matteo, PE

September 17, 2020

Outline

- What is the Health Index?
- Why We Developed the Health Index?
- What are Purpose and Use of the Health Index?
- Elements and Element Level Condition Data
- How is the Health Index Calculated?
- Concept of Damage Index
- Formula Modifying Factors
- Next Steps in Development Process
- Pause for Demonstration of Spreadsheet Tool & Expert Elicitation
- Additional and Future Uses

Reach out to Facility Managers for an Expert Elicitation

- $CS4_{equiv}$ weighting factors for CS2 & CS3
- $CS4_{equiv\text{-}max}$ per element
- DL (Design Life)
- FP (Functional Performance)
- OP (Operational Performance)
- SI (Safety & Importance Weighting)

What is the Health Index (HI)?

- The HI is a calculated index measuring the current overall condition of a structure on a 0 to 100 scale, with 100 corresponding to an ideal (new) structure
- HI for each element of a structure is calculated with detailed condition data from inspections and modified by:
  - Design Life (Age)
  - Functional Performance (Design Adequacy)
  - Operational Performance (Risk Consequence)
- Overall HI for each structure is calculated using the weighted average of the element HIs (weighted by safety and importance)
- The special structures HI aligns with the methodology used to calculate health index for conventional bridges

Why Have We Developed the Health Index (HI)?

- Performance measures and targets were established for bridges and pavements during the 2019 Comprehensive Review, but there were no readily available performance measures for tunnels and movable bridges
- Commissioner directed Structure & Bridge Division to develop a health index to measure condition and health of tunnels and movable bridges and for use as a performance measure
- Contacted several DOTs but none had yet developed a health index
  - Pennsylvania Dept. of Transportation (PennDOT)
  - Louisiana Dept. of Transportation & Development (La DOTD)
  - Washington State Dept. of Transportation (WSDOT)

What are Purpose and Use of the Health Index (HI)?

Immediate Use:

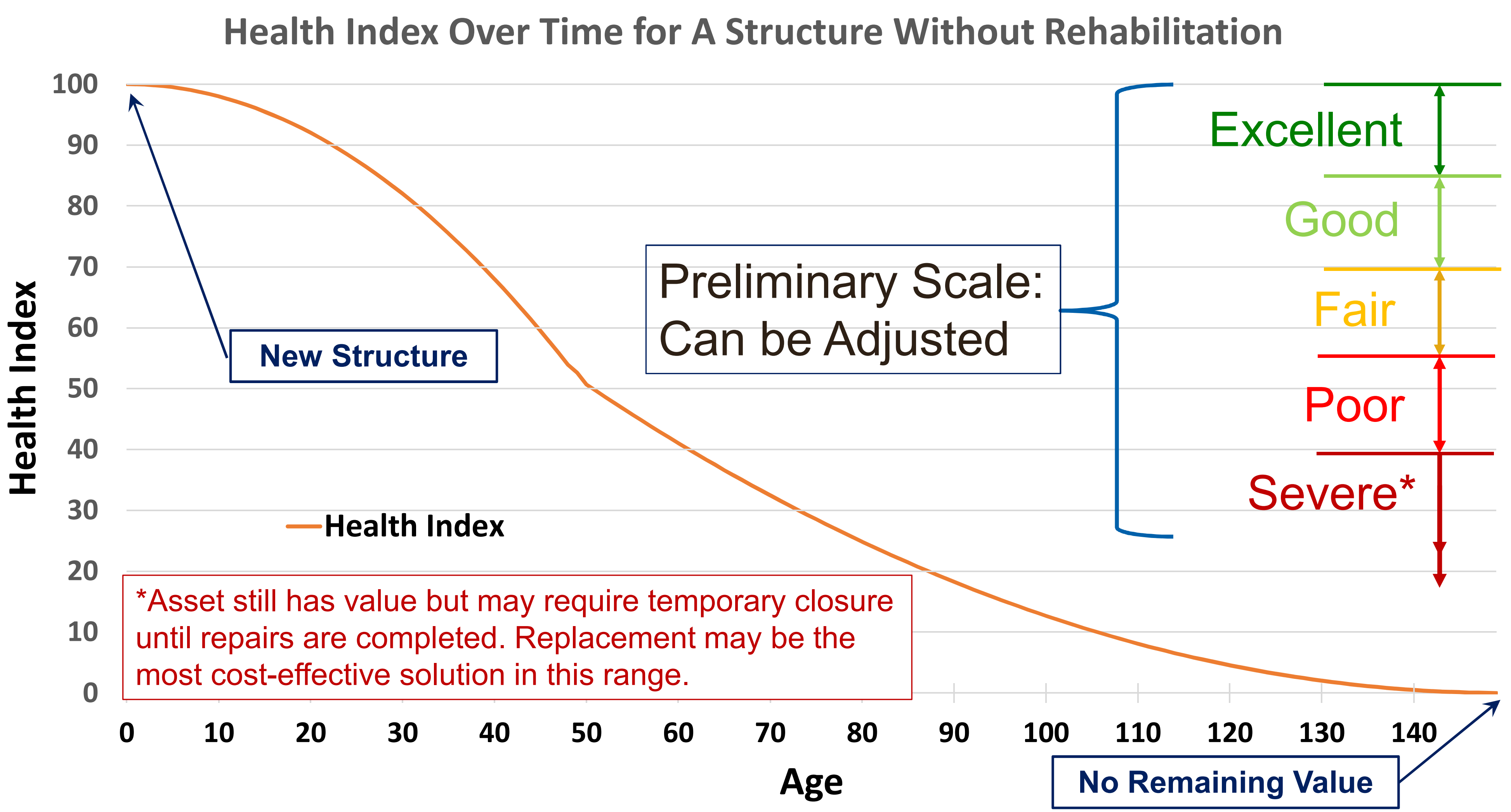
- Measure relative health of individual movable bridges and tunnels
- Measure relative health of individual systems (i.e. mechanical, electrical, structural, and operation/safety) for a given category of Special Structure.

Near Term Use:

- Use health index along with project prioritization formula for scenario analyses of 50 Year long term plan to maximize benefits with limited funds.

Long Term Use:

- Determine which treatments provide optimal life-cycle value.
- Possibly replace project prioritization formula with health index.

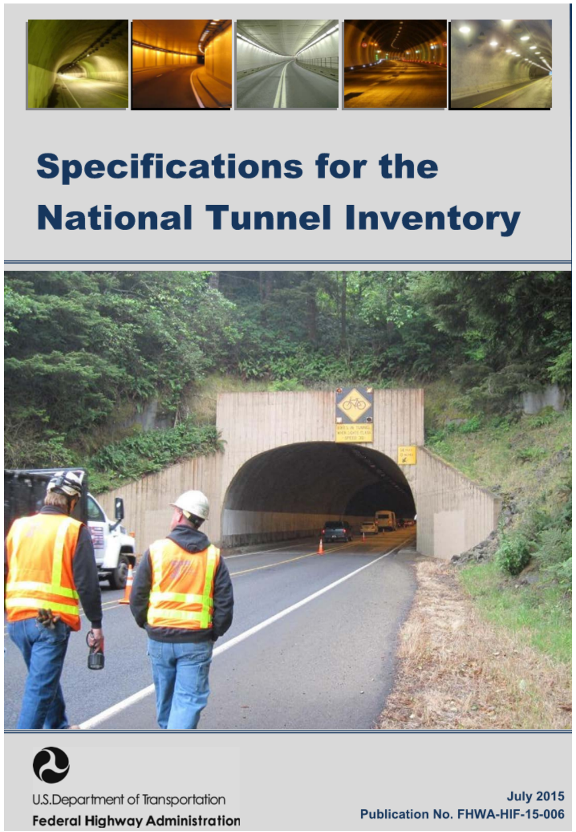


Health Index Over Time for A Structure Without Rehabilitation
Health Index
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Age
New Structure
Health Index
Preliminary Scale: Can be Adjusted
Excellent
Good
Fair
Poor
Severe*
*Asset still has value but may require temporary closure until repairs are completed. Replacement may be the most cost-effective solution in this range.
No Remaining Value

What is an "Element"?

Each structure has many elements in 4 major systems:

- Mechanical
- Structural
- Electrical
- Operational



At each field inspection, all elements receive a set of condition state (CS) ratings on a scale of 1 to 4 as follows:

- CS1 = Good
- CS2 = Fair
- CS3 = Poor
- CS4 = Severe

Examples of Tunnel Elements and Condition States Assigned During Inspection								
Element Number	Element Description	Units	Total Quantity	Condition State 1	Condition State 2	Condition State 3	Condition State 4	Group
10001	CIP Concrete Tunnel Liner	Sq Ft	605,740	587,128	5,349	13,261	2	Structural
10031	Concrete Cross Passageway	Ft	63	59	1	3	0	Structural
10041	Concrete Interior Walls	Sq Ft	159,664	159,618	9	37	0	Structural
10051	Concrete Portal	Sq Ft	31,333	29,526	1,804	3	0	Structural
10061	Concrete Ceiling Slab	Sq Ft	261,290	250,619	8,076	2,595	0	Structural
10111	Concrete Slab-on-Grade	Sq Ft	219,855	219,191	620	44	0	Structural
10140	Gaskets	Ft	24,185	16,204	7,071	415	495	Structural
10158	Asphalt Wearing Surface	Sq Ft	211,400	203,856	7,530	14	0	Operation & Safety
10161	Concrete Traffic Barrier	Ft	16,912	9,119	5,240	2,553	0	Operation & Safety
10170	Steel Pedestrian Railing	Ft	8,456	8,433	23	0	0	Operation & Safety
10200	Ventilation System	Each	2	0	2	0	0	Mechanical
10201	Fans	Each	24	0	23	1	0	Mechanical
10300	Drainage & Pumping System	Each	1	0	0	1	0	Mechanical
10301	Pumps	Each	1	1	0	0	0	Mechanical
10400	Emergency Generator System	Each	1	1	0	0	0	Electrical
10500	Electrical Distribution System	Each	1	0	1	0	0	Electrical
10550	Emergency Distribution System	Each	1	0	1	0	0	Electrical
10600	Tunnel Lighting Systems	Each	2	0	2	0	0	Operation & Safety
10601	Tunnel Lighting Fixtures	Each	1,304	1,268	8	28	0	Operation & Safety

How Condition States Are Assigned by Inspectors
Example: Fan Element (Mechanical System)

Condition State Definitions

Defect	Condition State 1	Condition State 2	Condition State 3	Condition State 4
Fan Operation (includes fan belt, fan chain, fan bearing temperature and/or fan drive temperature)	Operates on all speeds and in all modes with no noticeable temperature rise.	Operates on all speeds and in all modes. Requires manual restart or manual control to achieve this. Drive(s) require some adjustment. More than normal play observed. (If belt – minor wear/deterioration to belt.) Less than 40 degree F temperature rise form ambient temperatures during operation.	Fan operates on at least one speed or only operates in manual mode. Drive(s) require major adjustment. Severe play and/or belt/chain noise is observed. (If belt – moderate wear/deterioration to belt.) Between 40 degree F and 80 degree F temperature rise form ambient temperatures during operation.	Fan will not operate on any speed. Over 80 degree F temperature rise for ambient temperatures during operation.
Fan Condition	No notable distress.	Isolated breakdowns or deterioration.	The system is in poor condition – widespread deterioration or breakdowns reducing operational capacity, without impacting the serviceability of the element or tunnel.	The fan warrants evaluation to determine the effect on serviceability of the element or tunnel or the evaluation has determined there is an impact on the serviceability of the element or tunnel.

CS1 = Good
CS2 = Fair
CS3 = Poor
CS4 = Severe

Tunnel Safety Inspection Course

Course Number

FHWA-NHI-130110

Course Title

Tunnel Safety Inspection

This 5-day, Instructor-led Training (ILT) is highly interactive and builds upon participants' prior knowledge of tunnel and/ or bridge inspection. This course covers the entire breadth of knowledge necessary to manage or execute a successful tunnel inspection based on the National Tunnel Inspection Standards (NTIS), Tunnel Operations, Maintenance, Inspection and Evaluation (TOMIE) Manual and Specifications for the National Tunnel Inventory (SNTI). However, it does not replace the need for specialized experts to assist in inspections. There are nine instructional modules. Once participants display achievement of the learning outcomes of one module, the class will progress to the next module. During the course, the instructor will lead participants through a series of case studies giving them an opportunity to practice and apply their knowledge in real-life tunnel inspection situations. The capstone case study will be a virtual tunnel inspection that takes place in a computer-simulated, 3D environment. Using this tool, participants will be able to perform a tunnel inspection and demonstrate their achievement of all learning outcomes.

*Participant Prerequisite Requirement: ALL participants should successfully complete one of the following three prerequisite requirements:

-130054 Engineering Concepts for Bridge Inspectors; or

-130101 Introduction to Safety Inspection of In-Service Bridges; or

-130101A Prerequisite Assessment for Safety Inspection of In-Service Bridges.

Prior to taking this course, it is strongly recommended that participants complete 130055 Safety Inspection of In-Service Bridges, 130056 Safety Inspection of In-Service Bridges for Professional Engineers, or possess equivalent field experience.

It is not required, but strongly recommended that participants possess some design or safety inspection experience of in-service tunnels or bridges.

Tunnel Safety Inspection Course

130110 SESSION INFORMATION:

Start Date: 2/22/2021 **End Date: 2/26/2021** **Location: SALT LAKE CITY, UT**

Local Coordinator: Jeramiah Irick (307) 679-2801

Availability:	6 Public Seats	$480 Per Participant	Add To Cart
	1 FHWA Seats		Add To Cart

Start Date: 3/15/2021 **End Date: 3/19/2021** **Location: HONOLULU, HI**

Local Coordinator: John Williams (808) 587-2183

Availability:	6 Public Seats	$480 Per Participant	Add To Cart
	3 FHWA Seats		Add To Cart

Start Date: 7/12/2021 **End Date: 7/16/2021** **Location: LEBANON, OH**

Local Coordinator: Debbie Cox (614) 466-2307

Availability:	27 Public Seats	$480 Per Participant	Add To Cart
	2 FHWA Seats		Add To Cart

The Health Index is Calculated in 3 Steps

1. Determine the Condition-based Health Index of each element ($CHI_{element}$)
   - Uses detailed element condition data
   - Employs concept of a Damage Index (DI)
   - Applies a Design Life (DL) factor based on age of each element
2. Determine the Modified Health Index of each element ($MHI_{element}$)
   - Modifies the $CHI_{element}$ by two factors:
     - Functional Performance (Design Adequacy)
     - Operational Performance (Risk Consequence)
3. $MHI_{element}$ values for each element are weighted by Safety/Importance (SI) factors to calculate a HI for each structure and system on each structure (SI varies from 1 to 10)

Step 1: Condition-Based Health Index of each element ($CHI_{element}$)

1. $CHI_{element}$ is a function of the Damage Index (DI) and the age of the element
2. $CHI_{element} = DL*(1-DI_{element})$
   - Damage Index (DI) calculates the percentage of maximum acceptable deterioration that has occurred

$$DI_{element} = \%CS4_{equiv} \div \%CS4_{equiv\text{-}max}$$

   - $\%CS4_{equiv}$ is based on element level condition data
   - $\%CS4_{equiv\text{-}max}$ is derived from expert elicitation
   - DL = Design Life = 1.0 for new, 0.9 for midlife, or 0.8 for old

Step 1a: Determine Damage Index (DI) of each element

$$(DI_{element}) = (\%CS4_{equiv}) \div (\%CS4_{equiv\text{-}max})$$

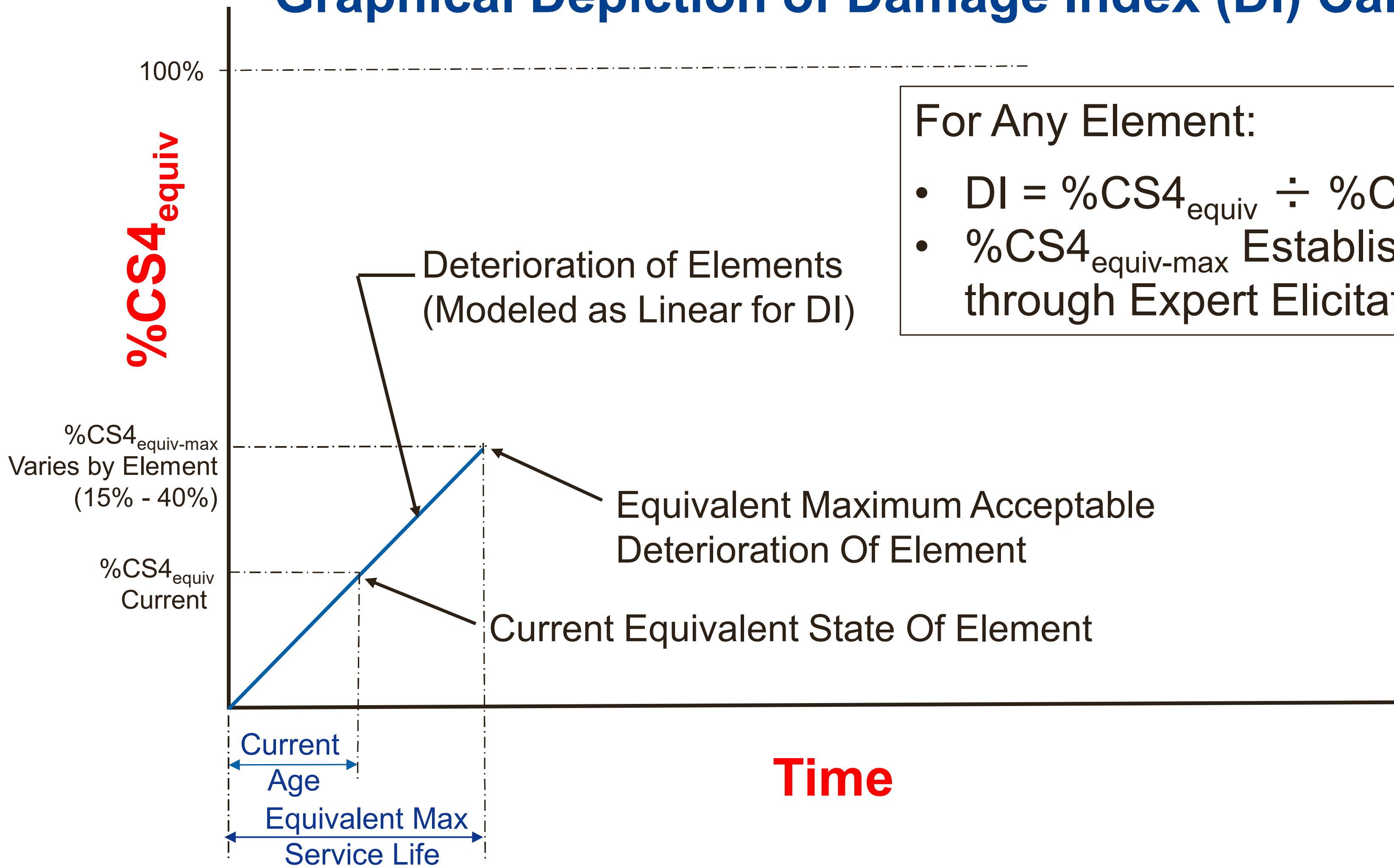
- **$\%CS4_{equiv}$ is the equivalent percentage in CS4**
  - $$\%CS4_{equiv} = \frac{(0.1*CS2_{quantity} + 0.4*CS3_{quantity} + 1.0*CS4_{quantity})}{\text{Total Quantity of Element}}$$
  - **Weighting factors for CS2 and CS3 can be varied where appropriate**
- **$\%CS4_{equiv\text{-}max}$ is the maximum tolerable percentage of an element that is in $CS4_{equiv}$ condition state. In other words, the amount of deterioration or damage at which a state of emergency is reached or replacement of the element is required.**

Step 1a: Example Damage Index (DI) Calculation

					Weighting Factor for $CS4_{equiv}$		
					0.1	0.4	1.0
Element Number	Element Description	Units	Total Quantity	Condition State 1	Condition State 2	Condition State 3	Condition State 4
10201	Fans	Each	16	1	9	3	3

- $CS4_{equiv}$ = [0.1*(9) + 0.4*(3) + (1.0)*3] ÷ 16 = 31.8%
- $CS4_{equiv\text{-}max}$ = 40% (Expert Elicitation)
- $DI_{element}$ = 31.8% ÷ 40% = 0.797

Graphical Depiction of Damage Index (DI) Calculation



For Any Element:

- DI = $\%CS4_{equiv} \div \%CS4_{equiv\text{-}max}$
- $\%CS4_{equiv\text{-}max}$ Established through Expert Elicitation

Step 1b: CHI of each element using DI and age factor (Design Life)

$CHI_{element} = DL*(1-DI_{element})$ where:

- DL = 1.0 for new
- DL = 0.9 for midlife
- DL = 0.8 for old

So, for the previous example:

- DL = 0.9 for midlife
- DI = 0.797
- $CHI_{element}$ = 100*(1-DI)*DL = 100*(1-0.797)*0.90 = 18

Step 2: Determine Modified Health Index for each element ($MHI_{element}$)

$MHI_{element} = (0.7 * CHI_{element}) + (0.15 * FP) + (0.15 * OP)$ where:

- FP = Functional Performance (Design Adequacy)
  - FP = 1.0 (excellent)
  - FP = 0.9 (good)
  - FP = 0.7 (adequate)
  - FP = 0.5 (marginal)
  - FP = 0.2 (poor*)
- OP = Operational Performance (Risk Consequence)
  - OP = 1.0 (insignificant consequence)
  - OP = 0.9 (minor consequence)
  - OP = 0.7 (moderate consequence)
  - OP = 0.4 (major consequence)
  - OP = 0.2 (catastrophic consequence)

---

*If a needed element is missing, it will affect the design adequacy of the existing elements performing a similar function

Step 3a: Health Index for Major System

$$HI_{system} = \frac{\Sigma(SI_{element} * MHI_{element})}{\Sigma SI_{elements}}$$

Where:

- $MHI_{element}$ = Modified HI for each element of the Major System
- $SI_{element}$ = Safety and Importance Weighting Factor for Each Element

Element Safety/Importance (SI) Factors

Element Safety & Importance Description	Factor
Key Element – High	10
Key Element – Medium	9
Key Element – Low	8
Major Element – High	7
Major Element – Medium	6
Major Element – Low	5
Minor Element – High	4
Minor Element – Medium	3
Minor Element – Low	2
Minor Element - Minimal Importance	1

Element Safety/Importance (SI) Factors - Definitions

Element	The element of the structure is designed to prevent inadvertent or hazardous utilization and operation.
Element Safety	Element Safety is the condition of the element of being safe from causing hurt, injury, or loss of structure's users or operators.
Element Importance	Element Importance rates the significance of the complete group of elements relative to the impact on the operation of the entire structure.
Key Element	Primary and/or most significant element(s) in the group of elements in the structure impacting the rating of the element regarding its Safety and/or Importance.
Major Element	Prominent or significant - but not a key element(s) - in the group of elements in the structure impacting the rating of the element regarding its Safety and/or Importance.
Minor Element	Very limited significant element(s) in the group of elements in the structure impacting the rating of the element regarding its Safety and/or Importance.
Minor Element - Minimal Importance	In-significant element(s) in the group of elements in the structure, not impacting the rating of the element regarding its Safety and/or Importance
High	Most importance and/or significance in the current Key, Major, or Minor group.
Medium	Average importance and/or significance in the current Key, Major, or Minor group.
Low	Minor importance and/or significance in the current Key, Major, or Minor group.

Step 3a: Health Index for Major System – Example Calculation

Calculating HI for the Mechanical System on a Tunnel						
Element Number	Element Description	System	Safety & Importance Category	Modified Health Index $MHI_{element}$	Safety & Importance Weight Factor (SI)	MHI*SI
10200	Ventilation System	Mechanical	Key Element - Low	0.38	8	3.07
10201	Fans	Mechanical	Key Element - Medium	0.45	9	4.01
10300	Drainage & Pumping System	Mechanical	Key Element - High	0.00	10	0.00
10301	Pumps	Mechanical	Key Element - Low	1.00	8	8.00
				Total	35	15.08
				HI_{system}	=100*(15.08 ÷ 35)	43

VDOT Virginia Department of Transportation

Step 3b: Health Index for Structure

$HI_{structure}$ is calculated in the same way as is done for each system (see previous slide for an example)

$$HI_{structure} = \frac{\Sigma(SI_{element} * MHI_{element})}{\Sigma SI_{elements}}$$

Where:

- $MHI_{element}$ = Modified HI for each element of the Structure
- $SI_{element}$ = Safety and Importance Weighting Factor for Each Element

Calculation Summary (Numbers are Preliminary Only)

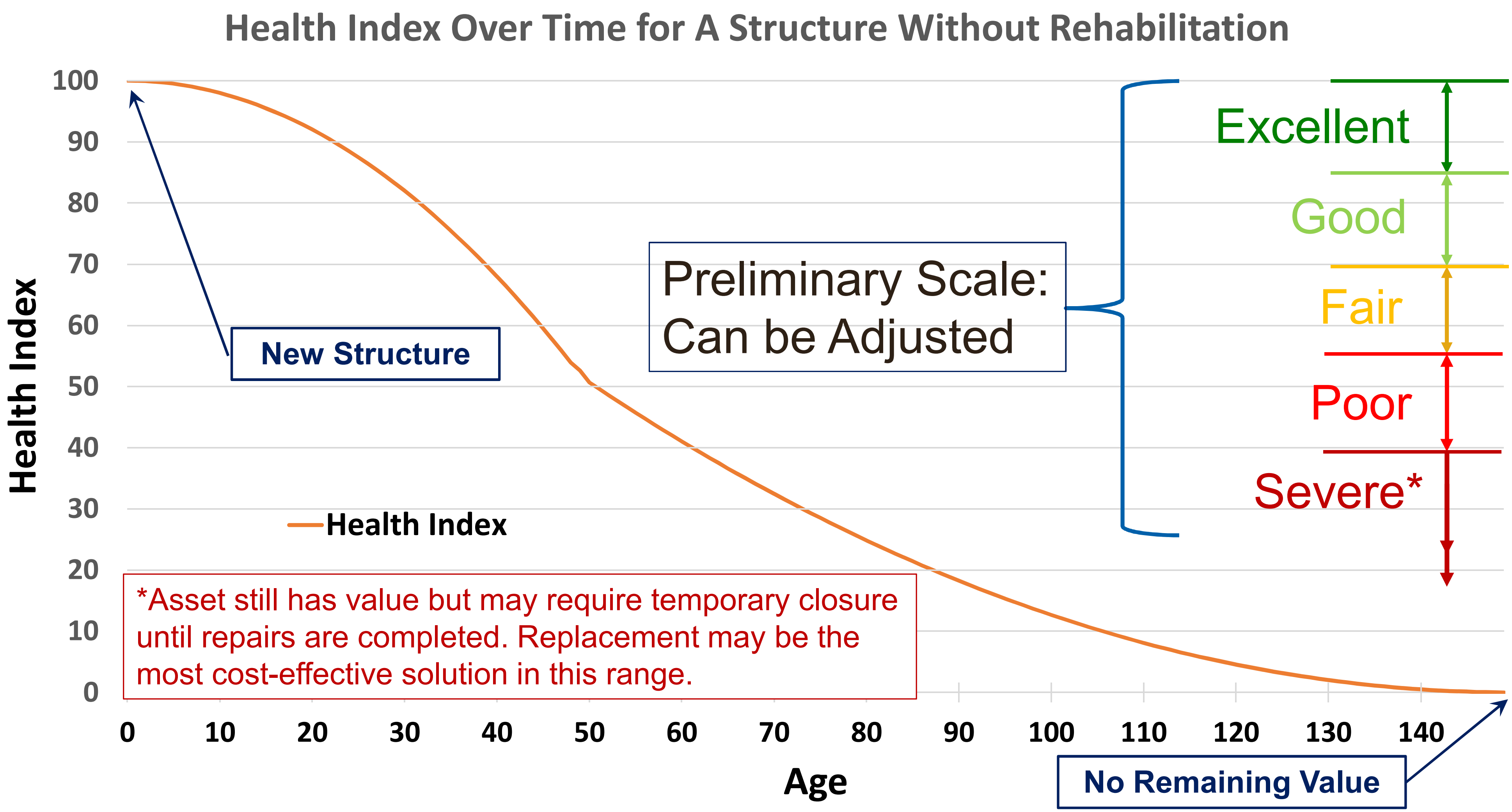
Summary of HI for Each System on Each Tunnel					
Tunnel	Electrical	Mechanical	Operation & Safety	Structural	Total
BWMT	53	43	72	84	**67**
ERMT	67	21	48	80	**52**
HRBT EBL	85	44	46	59	**54**
HRBT WBL	78	39	55	59	**55**
MMMBT	48	50	63	74	**64**
Rosslyn	0	50	50	78	**62**

Health Index Formula - Review

1. $CHI_{element}$ = Condition Health Index of an element = $DL*(1-DI_{element})$
   - where $DI_{element} = \%CS4_{Eq} \div \%CS4_{equiv\text{-}max}$
   - DL = 1.0 for new, 0.9 for midlife, or 0.8 for old
2. $MHI_{element}$ = Modified Health Index of an element
   - $MHI_{element} = (0.7*CHI_{element}) + (0.15*FP) + (0.15*OP)$, where:
   - FP = Functional Performance (Design Adequacy) varies from 1.0 to 0.2
   - OP = Operational Performance (Risk Consequence) varies from 1.0 to 0.2
3. MHI values are weighted by Safety/Importance (SI)
   - SI varies from 1 to 10 depending on the element
   - $HI_{system} = \Sigma(SI_{element}*MHI_{element})/\Sigma SI_{elements}$
   - $HI_{structure} = \Sigma(SI_{element}*MHI_{element})/\Sigma SI_{elements}$

Next Steps

1. Reach out to Facility Managers for an Expert Elicitation
2. Finalize Movable Bridge Spreadsheet Tool
3. Testing & Calibration – Review by Facility Managers
4. Reach out to AASHTO Bridges & Structures Technical Committees (T-8 Movable Bridges & T-20 Tunnels) for input



Health Index Over Time for A Structure Without Rehabilitation
Health Index
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Age
Health Index
New Structure
Preliminary Scale: Can be Adjusted
Excellent
Good
Fair
Poor
Severe*
*Asset still has value but may require temporary closure until repairs are completed. Replacement may be the most cost-effective solution in this range.
No Remaining Value

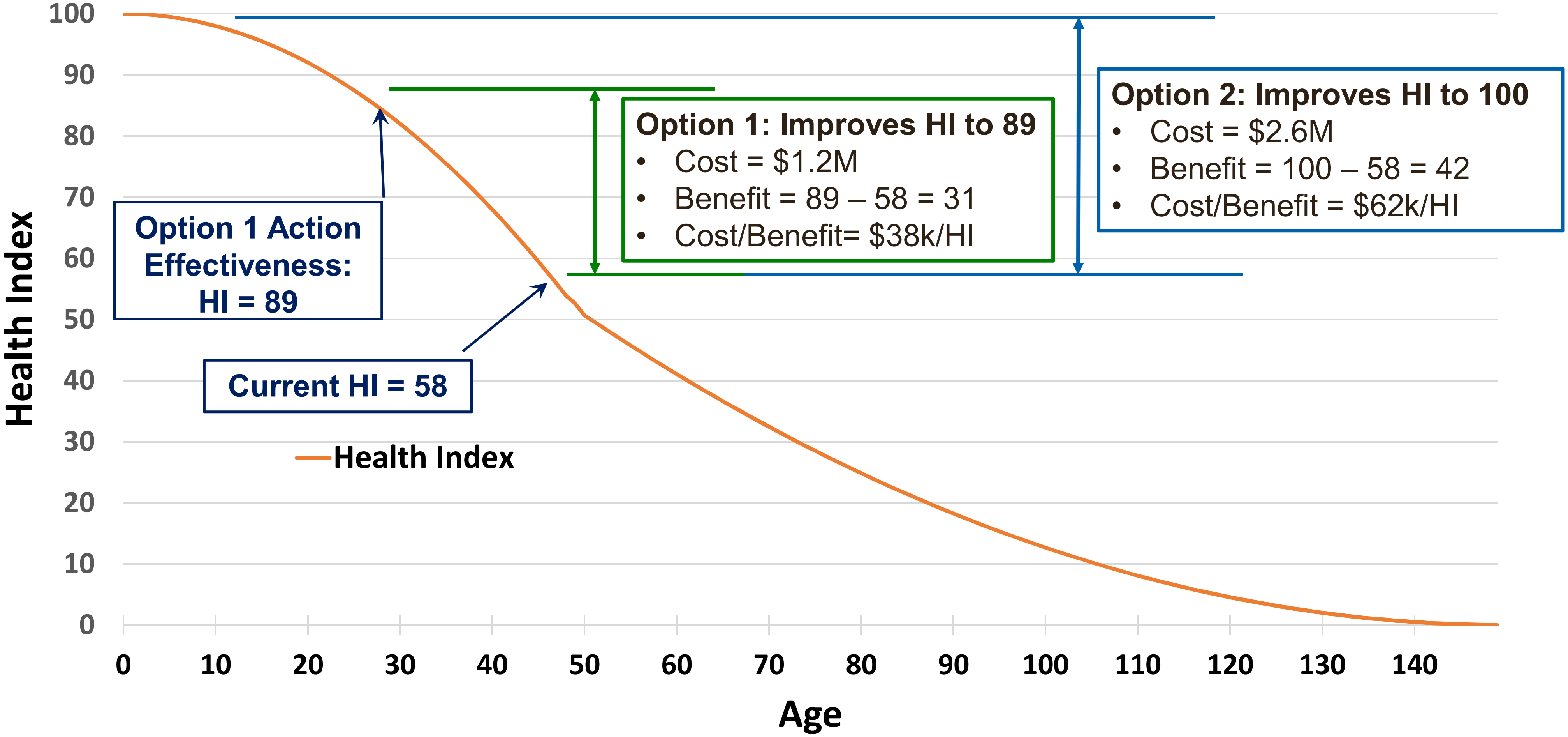
Pause for Demonstration of Tool & Expert Elicitation

1. Demonstration of Spreadsheet Tool
2. Expert Elicitation
   - $CS4_{equiv}$ weighting factors for CS2 & CS3
   - $CS4_{equiv\text{-}max}$ per element
   - DL (Design Life)
   - FP (Functional Performance)
   - OP (Operational Performance)
   - SI (Safety & Importance Weighting)

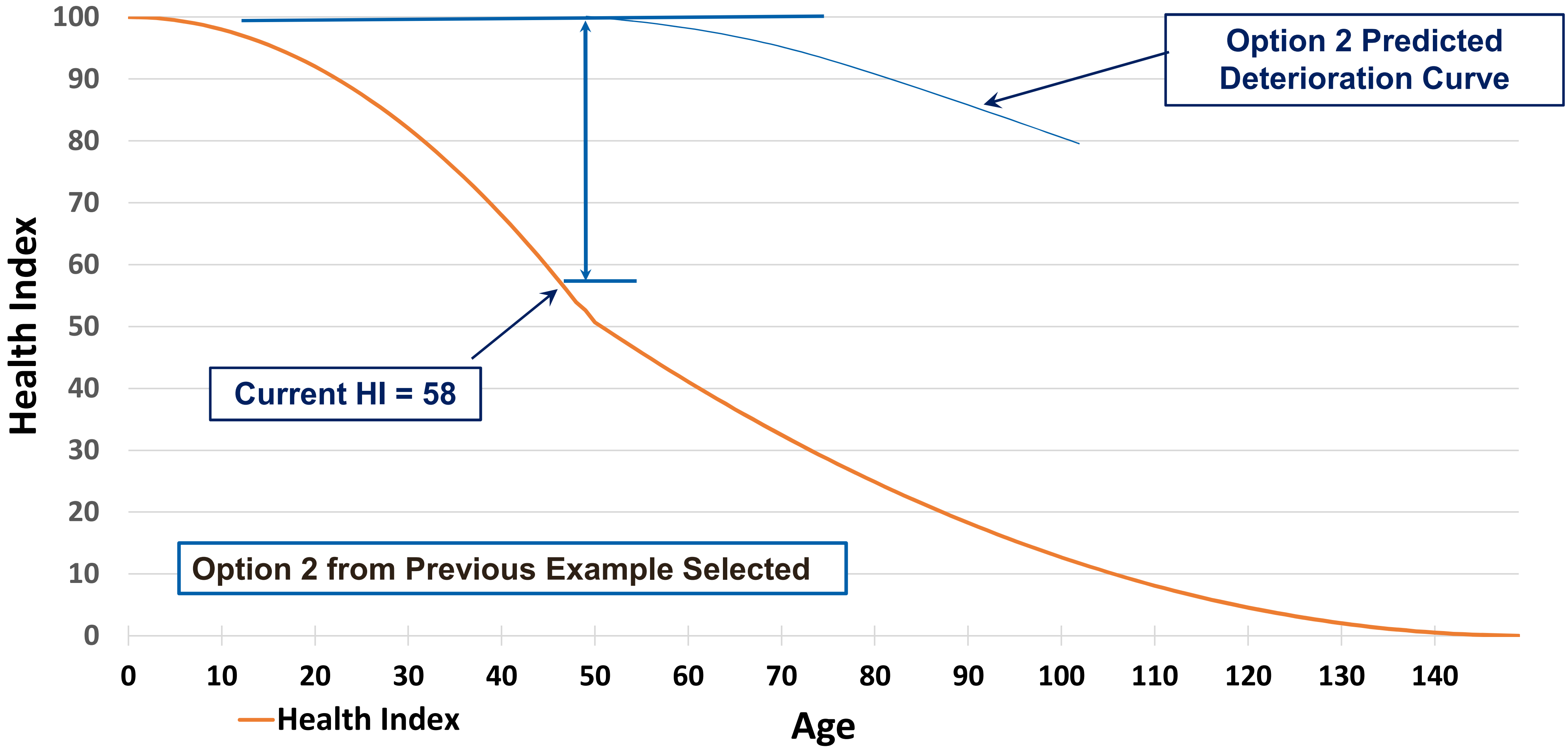
Additional and Future Uses of the HI

1. Calculate immediate cost/benefit of any action
    - Incorporates all the variables in prioritization formula, so an immediate "benefit" can be predicted
2. Predict future conditions
3. Calculate long term (life cycle) value of any action
4. Can eventually replace the prioritization formula for project selection

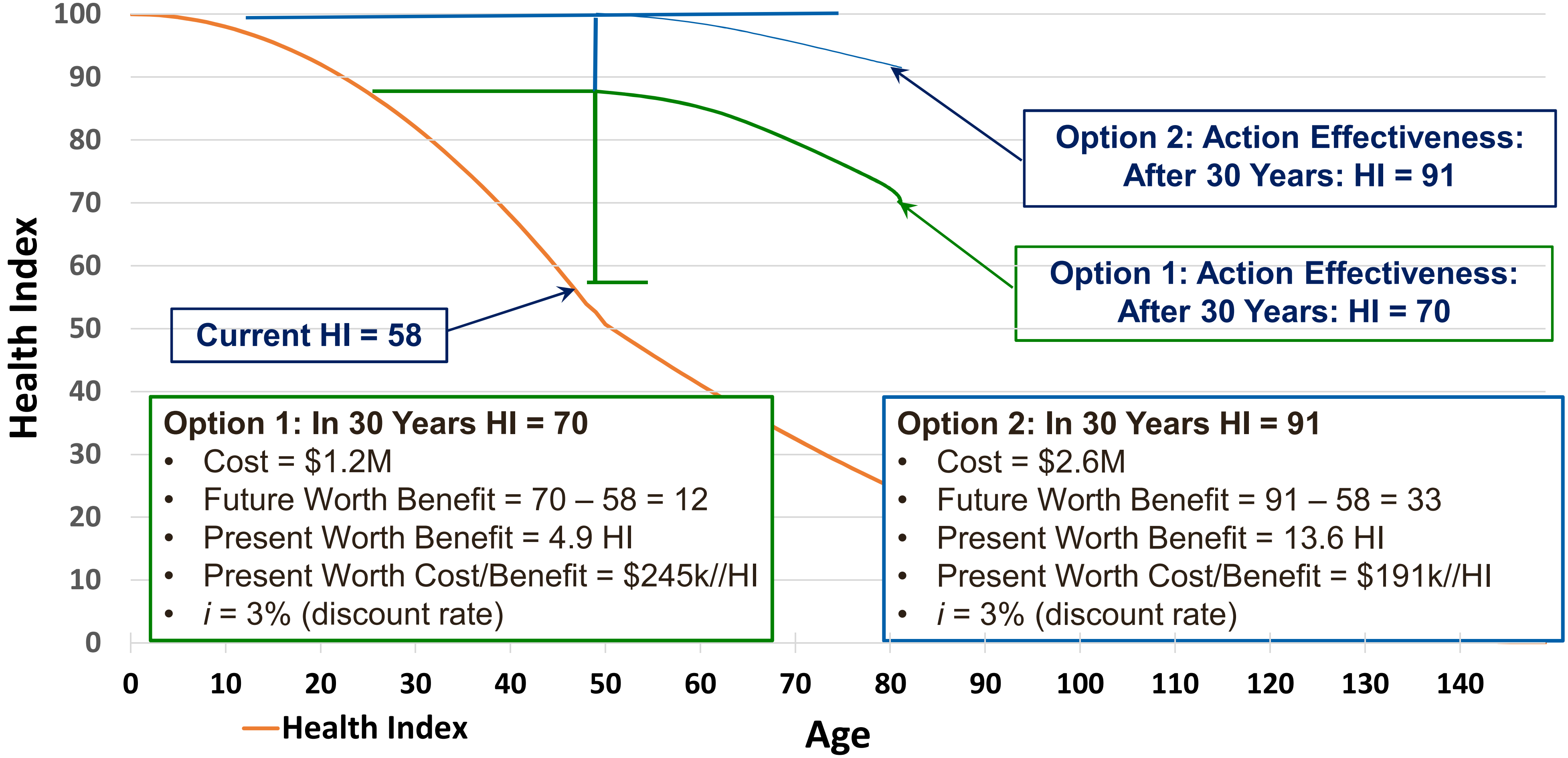
1. Using HI to Calculate Immediate Cost/Benefit Ratio



2. Using HI to Predict Future Conditions



3. Using HI to Calculate Life Cycle Cost/Benefit Ratio



4. Eventual Replacement of Existing Prioritization Formula with the HI

- The HI incorporates all the variables in the current prioritization formula, so the transition should be smooth
- Once the HI is tried out and well-established, it would make sense to move to one tool rather than multiple tools.
- The prioritization formula uses a great deal of judgement-based scores. HI removes that to the best extent possible
- By separating the cost factor from the non-cost factors, we can select projects by a cost/benefit ratio