Bridge Project Prioritization

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Kentucky Transportation Center
College of Engineering, University of Kentucky, Lexington, Kentucky

in cooperation with
Kentucky Transportation Cabinet
Commonwealth of Kentucky

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Bridge Project Prioritization

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16. Abstract

Kentucky's 14,000+ bridges are key nodes within the state's surface transportation network. They facilitate the movement of freight, commercial vehicles, and personal vehicles alike. Historically, the Kentucky Transportation Cabinet (KYTC) has prioritized bridge maintenance projects using sufficiency ratings. These ratings are based on three factors — structural adequacy and safety, design obsolescence, and an asset's importance within the roadway network. Although useful, sufficiency ratings do not account for factors that should be considered during the prioritization process (e.g., condition factors, risk). To address the shortcomings associated with using sufficiency ratings, KYTC — with the assistance of the Kentucky Transportation Center — has developed and implemented a new Enhanced Bridge Prioritization Index. Sixteen factors distributed across three categories (Condition, Mobility, and Risk) are used to calculate index scores for each structure. Each factor is weighted in proportion to its contribution to the overall index. The Condition category makes up the largest part of the index, accounting for 68% of the overall score. Scores range between 0 and 1. A bridge that receives a score of 0 is the lowest priority, while a bridge that earns a score of 1 ranks as the highest priority. Following successful testing, over the next few budget cycles KYTC intends to use the Enhanced Bridge Prioritization Index. As part of this effort, the agency will evaluate the index's performance and make revisions as needed.

17. Key Words
bridge, culvert, project prioritization, risk, maintenance

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Executive Summary

The Kentucky Transportation Cabinet's (KYTC) mission is to deliver a safe, efficient, environmentally sound, and fiscally responsible transportation system that provides economic opportunities and enhances the quality of life in Kentucky. KYTC's Department of Highways plays an indispensable role in achieving this mission by inspecting, maintaining, and improving the state's 14,000+ bridges (over 9,000 are state owned). Currently, bridge maintenance projects are prioritized based on sufficiency ratings and input from district personnel. Sufficiency ratings are based on three factors — structural evaluation, design obsolescence, and asset importance — and used to determine eligibility for federal funding. They provide an overall measure of bridge condition on a scale from 1 to 100. A score of 100 indicates a bridge is entirely sufficient (usually a new structure); a completely deficient bridge has a rating of 1.Despite their utility, sufficiency ratings omit variables that could justifiably be used to prioritize projects (e.g., risk, condition factors). This prevents KYTC from accurately ranking the relative importance of each bridge within the overall network. With the assistance of Kentucky Transportation Center (KTC) researchers, KYTC is instituting a new tool to overhaul the bridge prioritization process — the Kentucky Enhanced Bridge Prioritization Index. Adopting the index will strengthen the Cabinet's ability to prioritize bridge projects and enhance the resiliency of Kentucky's transportation networks.

To understand what methods are available for prioritizing bridge maintenance, the research team reviewed peer-reviewed literature and bridge prioritization indices used by other state transportation agencies. Typically, agencies rely on methodological frameworks that make extensive use of National Bridge Inventory data, especially items that represent a structure's physical condition and metrics that quantify the criticality of assets within local, regional, and statewide transportation networks. KTC then facilitated a series of workshops with KYTC subject-matter experts to determine what elements should be included in a new bridge prioritization index. The Cabinet's stakeholders followed the Analytic Hierarchy Process to establish the relative importance of each factor included in the Enhanced Bridge Prioritization Index. The index is calculated using data on 16 factors that are grouped into three categories — **Condition, Mobility, and Risk**. Each factor is assigned a weight that denotes its contribution to the overall score. Tables E1 – E3 list the contribution of each factor to the overall index score. For example, the Health Index accounts for 26% of a structure's score. Enhanced Bridge Prioritization Index scores range between 0 and 1, where 0 indicates the lowest priority and 1 the highest priority. Following successful testing using data from KYTC's bridge database, the Cabinet plans to use the new index to prioritize bridge projects over the next several budget cycles, giving the agency the chance to review its performance and update it as needed.

Table E1 Kentucky Enhanced Bridge Prioritization Index Weights — Mobility

Factor	Contribution to Overall Score
Detour length	0.51%
ADT	2.38%
ADTT	1.64%
Posting-weight	2.92%
School bus route	0.51%
Route classification- NHS	1.01%
Emergency Route Designation	0.53%

Table E2 Kentucky Enhanced Bridge Prioritization Index Weights — Risk

Factor	Contribution to Overall Score
Vertical clearance	1.62%
Scour criticality	9.57%
Fracture-critical	3.89%
Horizontal clearance	0.78%

Factor	Contribution to Overall Score
Existence of fatigue-prone details	3.85%
Frequency of inspection	1.77%

Table E3 Kentucky Enhanced Bridge Prioritization Index Weights — Condition

Factor	Contribution to Overall Score
Age	5.24%
NBI Condition Rating	37.29%
Health Index	26.49%

Chapter 1 Introduction and Background

1.1 Overview

Of the 14,000 bridges inventoried and inspected by the Kentucky Transportation Cabinet (KYTC) over 9,000 are state owned. Kentucky's bridges function as linchpins of the transportation network by facilitating freight movement and providing safe passage to drivers going to school, work, or home. Maintaining driver safety and mobility is vital to the transportation network.

Bridge maintenance projects are currently prioritized based on sufficiency ratings and input from KYTC district personnel. The Federal Highway Administration (FHWA) developed sufficiency ratings to determine eligibility for and prioritization of federal funding. These ratings are based on structural evaluation, design obsolescence, and asset importance. KYTC's *Bridge Inspection Procedures Manual* defines sufficiency rating as "an overall measure of a bridge's condition, used to determine eligibility for federal funds. Ratings are on a scale of 1 to 100, with 100 considered as an entirely sufficient bridge, usually new; an entirely deficient bridge would receive a rating of 1."[1] The Cabinet bases sufficiency ratings on 18 data items from its Structural Inventory and Appraisal (SI&A). Up to 55 points are awarded for *Structural Adequacy and Safety*, 30 for *Serviceability and Functional Obsolescence*, and 15 for *Essentiality for Public Use*.[2]

The conventional approach to sufficiency ratings is flawed because it omits factors which can justifiably be used to prioritize projects. By only focusing on structural evaluation, design obsolescence, and asset importance, ratings overlook factors such as risk and condition. Failing to incorporate risk and condition factors may prevent KYTC from accurately ranking the relative importance of bridge assets within the overall network. To address these issues, the Kentucky Transportation Center (KTC) worked with the Cabinet to integrate a new prioritization index into the rating process. The new index synthesizes bridge condition data and other factors to help KYTC prioritize projects and carry out risk-based asset management.

1.2 Research Objectives

- Identify other states using a Bridge Rating Index and review those approaches
- Conduct workshops to identify components of an index for KYTC. Develop and test the index.
- Refine index through several rounds of feedback

Table 1.1 Report Structure

Chapter	Material
2	• Literature review covering bridge management systems, bridge performance measures, and general prioritization approaches
3	• Provides background on bridge prioritization methods from the perspectives of the federal government and state transportation agencies as well as key takeaways
4	• Reviews the methodology used to develop the Kentucky Enhanced Bridge Prioritization Index
5	• Concluding thoughts and application of the Index

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[1] https://transportation.ky.gov/Maintenance/Documents/2017%20Bridge%20Inspection%20Procedures%20Manual.pdf

[2] http://datamart.business.transportation.ky.gov/

Chapter 2 Literature Review

Beginning in the 1980s bridge management systems were developed to optimize funding and inform decisions about structure replacement. The most popular of these systems today is Pontis, which was developed by FHWA in cooperation with state departments of transportation (DOTs) (Thompson et al. 1998). Efforts to improve bridge network optimization preceded the advent of robust development of bridge management systems. Farid et al. (1988) proposed adopting benefit-cost analysis to optimally allocate bridge project funds, while Hyman and Hughes (1983) used life-cycle costing to optimize repair or replacement decisions. The latter has proven to be a popular approach along with Markovian models. Later researchers proposed models and methods within this framework to optimize planning and performance (e.g. Jiang and Sinha 1989, Jiang et al. 1988, Vitale et al. 1996, Ravirala et al. 1996, Harper and Majidzadeh 1991, Jiang et al. 2000, Sobanjo et al. 1994, Frangopol et al. 2000, Harper et al. 1990, Guignier and Madanat 1999). Prioritization and optimization are not identical, however, there have been attempts to meld optimization and prioritization (Jiang and Sinha 1990). Many of these approaches have limitations, such as a lack of performance reliability, the failure of Markovian models to account for the entire history of deterioration, and system performance not being addressed as it should (Frangopol and Das 1999). Incorporating a reliability-based approach can ameliorate these issues, transitioning bridge management toward a system based on "lifetime reliability and whole-life costing" (Frangopol et al. 2001).

Integrating additional measures based on performance into decision making has become increasingly popular among agencies: "Bridge agencies have expressed a need to enhance current decision-making methodologies to include other performance criteria, such as bridge condition, safety, traffic flow disruption, and vulnerability (Patidar et al. 2007, p.1). Patidar et al. (2007) added performance measures to a utility optimization exercise that included (p. 1):

- Preservation of bridge condition
- National Bridge Inventory (NBI) condition ratings, health index, and sufficiency rating
- Traffic safety enhancement
- Geometric and inventory/operating rating
- Protection from extreme events
- Vulnerability ratings for scour, fatigue/fracture, earthquake, collision, overload, and other human-made hazards
- Agency cost minimization
- Initial cost, life-cycle agency cost
- User cost minimization
- Life-cycle user cost

Bridge performance measures have tended to reflect agency goals (Chase et al. 2016). Weykamp et al. (2009, p. 14-2) observed that "Performance measures are network-level values that show the fitness of bridge networks and, over time, the achievements of bridge programs." Performance measures can be integrated into prioritization activities by using risk measures (e.g., scour, seismic vulnerability).

Attempts to prioritize bridge projects date to at least the 1980s. Arner et al. (1986) reviewed the approach of a Pennsylvania working group tasked with ranking maintenance activities and prioritizing bridges, evaluating bridge deficiencies and associated costs, and providing information to manage state bridges in a cost-effective manner. Boyce et al. (1987) developed two indices to prioritize bridge projects: Structural Safety, focused on deterioration and using a combination of element condition ratings, and Geometric Safety, which related bridge geometrics to crash data. Prioritizing limited funds across maintenance and rehab projects remains challenging for DOTs (Das 1999).

Common measures used to prioritize bridge projects include structural condition, geometric issues, scour and flood vulnerability, corridor improvement, and in some states fracture, collisions, and fire (Patidar et al. 2007). Health indices or some indication of bridge structural condition are preferred methods of quantifying performance sufficiency ratings given that agencies focus on minimizing life cycle costs (Patidar et al. 2017). Another method of ranking bridge projects is a defect-based urgency index that focuses on defective structural elements (e.g., surface, deck top, deck bottom, and drainage system) and their level of criticality (Dabous et al. 2016). Inkoom and Sobjano (2019) evaluated how bridge elements impact overall reliability, the effects of critical elements on deterioration, methods for ranking elements, and the consequences that might result from failing to allocate resources optimally. Based on 20 years of data, they identified the superstructure and substructure elements as critical bridge features. This is similar to findings using element failure time distributions and repair rates that found the superstructure is more important to deterioration than other elements (Inkoom and Sobanjo 2018). Any prioritization process must be consistent with an agency's goals for addressing deficient bridges, ensure preventive maintenance is done on bridges in good condition, address overall network performance, and account for risk (Weykamp et al. 2009). Inspectors and maintenance crews can identify priority issues for review by central office staff. Generally, priority indicators include condition ratings, structurally deficient bridges, and similar factors.

The importance of resilience and its role in managing bridge networks remains a hotly contested topic. Resilience can be measured based on factors like geology, seismology, regional conditions, and resilience to potential damage or element failure. In Washington Malone et al. (2005) developed a method to prioritize bridges for inspection after a seismic event based its magnitude and epicenter, bridge location, year of construction, and bridge type. Cost-benefit calculations have been used in Oregon to prioritize bridges for seismic retrofit (Mehary 2018). Babaei and Hawkins (1991) proposed a prioritization scheme for seismic retrofitting bridges based on vulnerability and the bridge's importance within the broader transportation network. Basoz and Kiremidjian (1995) advanced a similar method that uses criteria such as public safety, importance of the bridge to the network, and the socioeconomic well-being of the area. Bridges in Virginia have been prioritized based on factors related to underwater inspections, including past inspections, corrosion, age, and traffic volume (McGeehan and Samuel 1993). Another method for prioritizing bridge projects is grouping important connectors and segments that have experienced damaging events in the past and then prioritizing projects that will maximize resilience while minimizing cost (Bocchini and Frangopol 2010). Scour[3] assessments can also be used to identify and prioritize bridges in need of countermeasures (Haas et al. 1999) and the risk to bridge foundations (Stein et al. 1999).

Risk assessment and management can also be integrated into the prioritization process. From a risk management perspective determining what can mitigated and the tradeoffs among various decisions can facilitate resource allocation (Ezell et al. 2000, Hastak and Baim 2001). Moon et al. (2009) developed a risk-based approach for prioritizing bridge projects focused on the probability of a hazard, exposure resulting from failure of a structure to perform as designed, and uncertainty. Decisions are made based on whether an agency deems the calculated risk level acceptable. Monitoring bridge health can be an element of sound bridge management, reducing maintenance costs and improving quality while helping to prioritize those activities (Alampalli and Ettouney 2006). Structural monitoring has also been used to generate data to assist planning and prioritization processes for inspection, rehab, maintenance, and repair (Ko and Ni 2005).

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[3] For a more comprehensive review of state DOT approaches to managing and mitigating scour risk see NCHRP Project 20-68A, Scan 15-02 (Curtis et al. 2017).

Chapter 3 Background and State Review

3.1 Background

In response to the collapse of the Silver Bridge in Point Pleasant, West Virginia, the Federal-Aid Highway Act of 1968 required the establishment of National Bridge Inspection Standards (NBIS). The Surface Transportation Assistance Act of 1978 mandated that public bridges longer than 20 feet be inventoried and inspected, culminating in the National Bridge Inventory (NBI).[4] NBIS have been revised several times, most recently in 2009.[5] Historically, designations such as *structurally deficient* have been applied to bridges. Structurally deficient bridges have elements that need to be monitored or repaired and have some restrictions associated with their use. *Functionally obsolete* bridges were built according to standards no longer in use — they may "not have adequate lane widths, shoulder widths, or vertical clearances to serve current traffic demand, or those that may be occasionally flooded."[6] KYTC's *Bridge Inspection Procedures Manual* defines criteria for classifying a bridge as structurally deficient or functionally obsolete (Table 3.1), although FHWA no longer tracks structurally deficient or functionally obsolete bridges.

Table 3.1 NBI Condition Definitions

Bridge Condition	Criteria
Structurally Deficient (one or both apply)	1. Condition rating of 4 or less for one or more of the following condition rating items: • Item 58 (Deck)[7] • Item 59 (Superstructure) • Item 60 (Substructure) • Item 62 (Culverts)
	2. Appraisal rating of 2 or less for one or both of the following appraisal rating items: • Item 67 (Structural Evaluation) • Item 71 (Waterway Adequacy)
Functionally Obsolete (one or both apply)	1. Appraisal rating of 3 or less for one or more of the following appraisal items: • Item 68 (Deck Geometry) • Item 69 (Underclearances, Vertical and Horizontal) • Item 72 Approach Roadway Alignment)
	2. Appraisal ratings of 3 or less for one or both of the following appraisal items: • Item 67 (Structural Condition) • Item 71 (Waterway Adequacy)

Table 3.2 presents descriptions for each NBI rating (see Virginia DOT[8] and Pennsylvania DOT[9]).

Table 3.2 NBI Condition Ratings

Rating	Description
9	Excellent condition
8	Very good condition: no problems noted
7	Good condition: minor problems
6	Satisfactory condition, structural elements show some minor deterioration

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[4] https://www.fhwa.dot.gov/bridge/nbi.cfm

[5] https://www.fhwa.dot.gov/bridge/nbis.cfm

[6] https://www.virginiadot.org/info/resources/bridge_defs.pdf

[7] For a listing of all codes see: https://www.fhwa.dot.gov/bridge/bripub.cfm

[8] http://www.virginiadot.org/info/resources/bridge_condition_key.pdf

[9] https://www.penndot.gov/ProjectAndPrograms/Bridges/Pages/Bridge-FAQs.aspx#:~:text=Bridge%20condition%20is%20determined%20by,of%20a%20bridge%20or%20culvert.&text=If%20the%20lowest%20rating%20is,6%20are%20classified%20as%20Fair.

Rating	Description
5	Fair condition: all primary structural elements are sound but may have some minor section loss (due to corrosion), cracking, spalling (deterioration of concrete surface) or scour (erosion of soil).
4	Poor condition: advanced section loss, deterioration, spalling or scour
3	Serious condition: Loss of section, deterioration, spalling or scour have seriously affected primary structural components. Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present.
2	Critical condition: advanced deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present or scour may have removed substructure support. Unless closely monitored it may be necessary to close the bridge until corrective action is taken.
1	Imminent failure condition: major deterioration or section loss present in critical structural components or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic but corrective action may put back in light service.
0	Failed condition: out of service, beyond corrective action

As part of the 2015 Fixing America's Surface Transportation (FAST) Act, FHWA published *The National Performance Management Measures; Assessing Pavement Condition for the National Highway Performance Program and Bridge Condition for the National Highway Performance Program Final Rule*. This rule contains guidelines on developing performance measures for National Highway System (NHS) pavements and bridges[10] and meets requirements initially defined in 2012's Moving Ahead for Progress in the 21st Century (MAP-21) Act. As part of this process FHWA changed the way it designates bridges, shifting away from terms like *structurally deficient* to ratings of good, fair, or poor. Ratings are assigned based on the lowest condition rating.[11]

Bridges now designated as *poor* are roughly equivalent to those previously labeled structurally deficient. The ratings assigned under different systems are relatively transferable, which enables longitudinal analysis. Each bridge component — deck, superstructure, and substructure — is scored using NBI's 1 – 9 ranking system (Table 3.2). A bridge's overall rating is based on which of those three elements receives the lowest score. For example, if a bridge's deck and superstructure both receive a score of 8 and the substructure receives a score of 7, the bridge's overall rating is 7. For culverts, overall condition is based entirely on the score of NBI Item 62 (Culverts). Corresponding NBI Conditions with the new ratings are shown in Table 3.3.

Table 3.3 NBI Condition Ratings and Bridge Condition

NBI Condition Rating	Bridge Condition
Greater than or equal to 7	Good
5-6	Fair
Less than or equal to 4	Poor

The new performance measures are based on the percentage of NHS bridges by deck area[12] classified as being in good and poor condition. State DOTs must set targets for all NHS bridges with two- and four-year goals and issue progress reports.

FHWA maintains several sources that house data on bridge conditions. The NBI aggregates data on bridges across the US. In 2019 the agency debuted the Long-Term Bridge Performance (LTBP) InfoBridge, a platform which lets users conduct detailed analysis of bridge data.[13] This program is a "long-term research effort to collect high-quality bridge data from a representative sample of highway bridges nationwide that will help the bridge community to

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[10] https://www.fhwa.dot.gov/tpm/pubs/PM2BridgeFactSheet.pdf

[11] https://www.fhwa.dot.gov/bridge/britab.cfm

[12] Deck area is calculated using structure length and deck width or approach roadway width; these are NBI items 49, 52, or 32.

[13] https://infobridge.fhwa.dot.gov/Home

better understand bridge performance."[14] Data on Kentucky bridges can be retrieved from LTBP InfoBridge and used to identify state-owned bridges as well as those located on specific route types (e.g., interstates, NHS routes, non-NHS routes). Figure 3.1 captures the percentage of all Kentucky bridges in good, fair, or poor condition for the 2010 – 2020 period, while Figure 3.2 presents the same data for only state-owned bridges. Appendix A contains detailed rating breakdowns by route type. Because all interstate bridges and practically every NHS bridge are state-owned, we only use one figure for those route types.

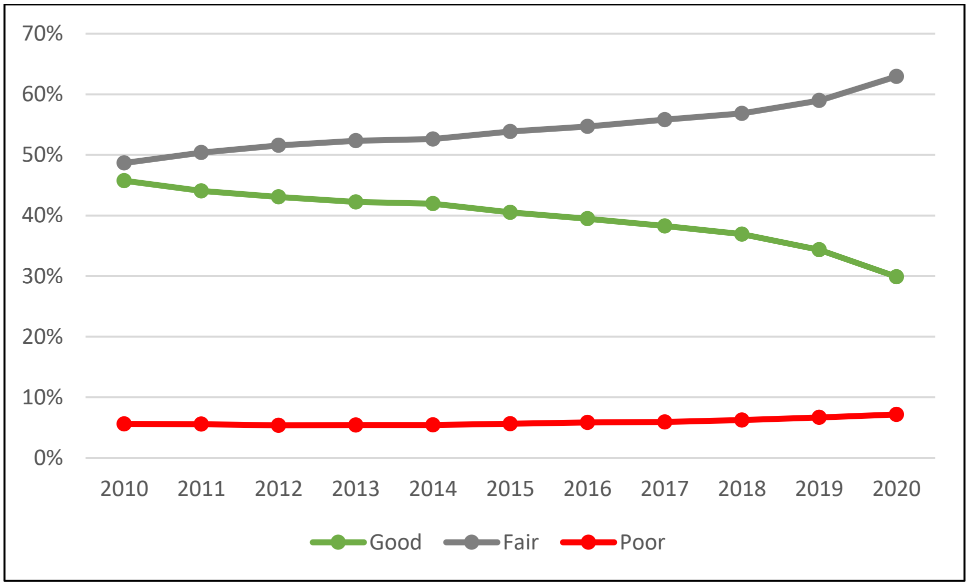

Figure 3.1 All Kentucky Bridges Condition

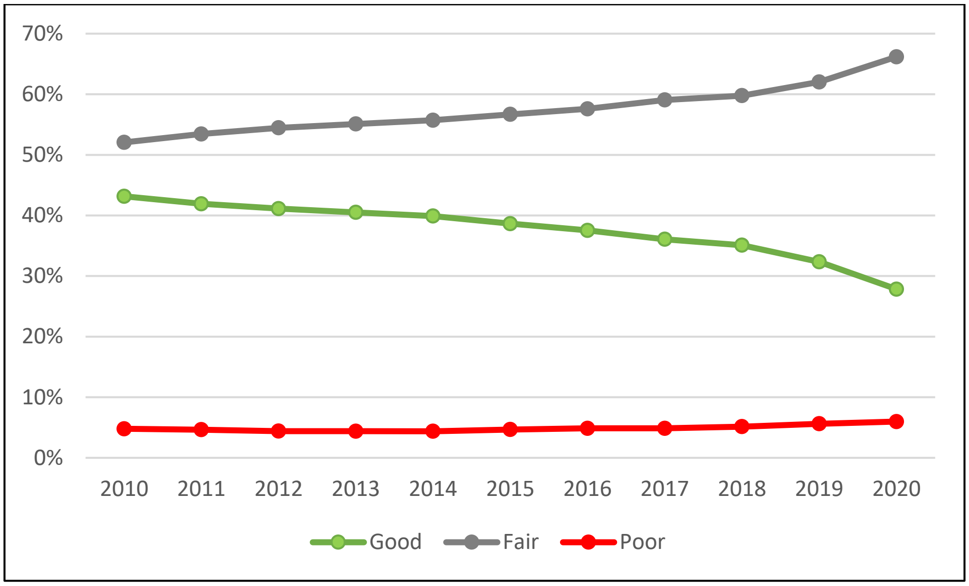

Figure 3.2 Kentucky State-Owned Bridges Condition

3.2 Bridge Rating and Prioritization Methods

This section reviews bridge rating and prioritization methods that have been proposed or implemented in 11 states. Some methods are used to prioritize projects at the statewide level, while others have been developed for local bridge programs to help municipalities and local governments fund rehabilitation and replacement projects (e.g.,

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[14] https://www.fhwa.dot.gov/publications/research/infrastructure/structures/ltbp/18008/18008.pdf

Ohio, Texas). Most of the frameworks rely on straightforward processes and equations to rank projects, and rely primarily on NBI data. The most common bridge management system is Condition Rating, or General Condition Rating. Condition Rating is assigned based on the lowest rating from the NBI. New York[15], Illinois (Ansari et al., 2004), and Tennessee[16] use this system. Most systems emphasize the physical condition of structures and their importance within highway networks (as quantified using metrics such as average daily traffic (ADT) and detour lengths). We focus on methods that facilitate programming decisions by explicitly ranking or assigning a level of importance to bridge assets.

3.2.1 Minnesota

Minnesota DOT (MnDOT) has adopted a risk-based approach to make decisions about repairing and replacing structures. When selecting projects for inclusion in the Capital Highway Investment Plan, the agency screens bridges based on its Bridge Replacement & Improvement Management (BRIM) tool, expert reviews, and NBI scores for the deck, substructure, and superstructure. BRIM includes a Bridge Planning Index (BPI) for calculating risk. It treats risk as the product of the likelihood of a service interruption and the consequences of a service interruption. Considerations like structural fatigue, bridge length, traffic characteristics, vulnerability to damage from flooding and trucks, and detours influence BPI scores. BRIM pinpoints bridges that require attention, needed work types, estimated costs, and service interruption risks. It takes advantage of inspection and inventory data to forecast replacement/improvement needs for each structure based on deterioration models. Once candidate projects have been identified, structures are evaluated using the scoring rubric presented in Table 3.4. Scoring is based on four criteria — condition, risk of service interruption (derived from the BPI), remaining service life, and deck area. Each structure receives a score ranging from 0 to 100, with higher scores indicating a higher priority. MnDOT applies distinct but similar scoring methods to culverts, bridges which carry railroads over state highways, and pedestrian bridges/underpasses.[17]

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[15] https://www.dot.ny.gov/main/bridgedata

[16] https://www.tn.gov/tdot/structures-/tennessee-bridge-facts.html

[17] Scoring rubrics are accessible via https://www.dot.state.mn.us/projectselection/bridge-method.html.

Table 3.4 Minnesota DOT Bridge Scoring Method

Criteria	Points Available	Scoring Rubric — Re-Decks, Rehabilitations, Replacements	Scoring Rubric — Overlays
Condition	50	*NBI Deck, Superstructure, or Substructure Rating* • ≤ 4 — 50 points • = 5 and/or fracture critical — 35 points	*NBI Deck Rating* • ≤ 6 — 50 points • = 7 — 30 points
Risk of Service Interruption	20	*Bridge Planning Index* • ≤ 60 — 20 points • 61 – 80 — 10 points • > 80 — 0 points	*Bridge Planning Index* • ≤ 60 — 20 points • 61 – 80 — 10 points • > 80 — 0 points
Remaining Service Life	20	*Deck Remaining Service Life* • ≤ 10 years — 20 points • 11 – 15 years — 10 points • > 15 years — 0 points	*Deck Remaining Service Life* • ≤ 20 years — 20 points • 21 – 30 years — 10 points • > 30 years — 0 points
Bridge Size	10	*Deck Area (ft^2)* • ≥ 100,000 — 10 points • 90,000 – 99,999 — 9 points • 80,000 – 89,999 — 8 points • 70,000 – 79,999 — 7 points • 60,000 – 69,999 — 6 points • 50,000 – 59,999 — 5 points • < 50,000 — 0 points	*Deck Area (ft^2)* • ≥ 100,000 and/or span length > 250 ft. — 10 points • 90,000 – 99,999 — 9 points • 80,000 – 89,999 — 8 points • 70,000 – 79,999 — 7 points • 60,000 – 69,999 — 6 points • 50,000 – 59,999 — 5 points • < 50,000 — 0 points

3.2.2 Arizona

Arizona DOT's (ADOT) bridge prioritization process uses data on 20 NBI items to prioritize funding and programming of eligible projects (ADOT 2016, 2020). Data used include information on structural condition, traffic characteristics, and sensitivity to hydraulic disturbances:

- NBI Items — 29, 109, 19, 58, 59, 60, 27, 64, 26, 51, 92A, 113, 53/54, 55/56, 71, 72, Deficiency Classification, Sufficiency Rating, Elevation

A weighting factor ranging from 0 to 1 is applied to raw data for each item based on the criteria listed in Table 3.5. For example, if a bridge's (ADT) is between 0 and 200, the weighting factor is 0.25; if a bridge's ADT exceeds 6,500, the weighting factor is 1. A bridge's priority ranking is computed using Eq. 1. The maximum score possible is 20. A higher score indicates higher priority.

$$\text{Bridge Priority Ranking} = \sum_{i=1}^{i=20} \text{NBI}_i \times \text{Weighting Factor}_i \qquad \text{(Eq. 1)}$$

Every year ADOT's Multimodal Planning Division coordinates the performance-based Planning to Programming (P2P) process to update the statewide prioritized project list. Prospective projects across different investment categories (e.g., pavement preservation, bridge preservation, expansion projects) are ranked by ADOT's technical groups based on scores in up to four categories — technical score, policy score, safety score, and district score.

Bridge projects are ranked based on their technical (60%), policy (10%), and district scores (30%). Technical scores are derived from inspection and assessment data and normalized using a 60-point scale. The highest-ranking bridge receives the maximum score of 60 points. Projects rankings are established using Eq. 2:

$$\text{Bridge Preservation Technical Score} = \left((1 + \text{n}) - \text{x}\right) \times \text{y} \qquad \text{(Eq. 2)}$$

where:
x = rank order
y = weighted district score percentage
n = 100 (maximum number of projects considered)

Budget limitations restrict application of this formula to the top-100 project recommendations. Three components factor into policy scores: freight flow (percentage of average annual daily traffic [AADT] consisting of freight vehicles), corridor significance/functional classification, and local funding contributions. District scores are the product of rankings generated by district engineers and their staff. The Draft Final P2P list ranks projects in each investment category.

Table 3.5 Arizona DOT Bridge Prioritization Weighting Factors

NBI Item	Weighting Factor			
	0.25	**0.50**	**0.75**	**1.00**
29 — ADT	0 – 200	201 – 1,000	1,001 – 6,500	> 6,500
109 — % Truck Traffic	0 – 5	6 – 10	11 – 15	> 15
41 — Weight Restricted	B (Open posting recommended but not implemented)	D (Open posted or closed if not for shoring)	P (Posted)	K (Closed)
19 — Detour Length	0 – 5 miles	6 – 10 miles	11 – 15 miles	> 15 miles
58 — Deck Condition	6	5	4	< 4
59 — Superstructure Rating	6	5	4	< 4
60 — Substructure Rating	6	5	4	< 4
27 — Year Built	1980 – 1990	1970 – 1979	1960 – 1969	< 1960
64 — Operating Rating	31 – 35 tons	26 – 30 tons	20 – 25 tons	< 20 tons
26 — Functional Classification	Local	US Route	State Route	Interstate
51 — Bridge Deck Width	—	—	—	Substandard
92A — Fracture Critical Member Present	—	—	—	Yes
113 — Scour Critical Bridges	—	—	—	Yes
53 & 54 — Vertical Over/Under Clearance Deficiency	—	—	—	Yes
55 & 56 — Horizontal Clearance Deficiency	—	—	—	Yes
71 — Waterway Adequacy	—	—	—	Inadequate
72 — Approach Roadway Alignment Deficiency	—	—	—	Yes
Deficiency Classification	—	—	—	Structurally Deficient or Functionally Obsolete
Sufficiency Rating	80 – 70	70 – 60	60 – 50	< 50
Elevation	—	—	—	> 4,000 ft. or using deicing material

3.2.3 Virginia

Virginia DOT (VDOT) uses its State of Good Repair prioritization formula to prioritize bridge projects (VDOT 2018). The formula incorporates five factors to arrive at a priority score for each bridge (Table 3.6). Each factor is multiplied by a weight — indicated by the coefficients a, b, c, d, and e — and then summed (Eq. 3). Coefficient values are not necessarily static as VDOT can adjust them when agency goals shift.

$$\text{Priority} = \text{a}(\mathbf{IF}) + \text{b}(\mathbf{CF}) + \text{c}(\mathbf{DRF}) + \text{d}(\mathbf{SCF}) + \text{e}(\mathbf{CEF}) \qquad \text{(Eq. 3)}$$

where:
a = 0.30; b = 0.25; c = 0.15; d = 0.10; e = 0.20

While Table 3.5 provides high-level summaries of each factor, it is worth identifying variables which go into their respective calculations. The IF is computed using data on current and future ADT, truck ADT percentages, a bypass factor which measures the impact of detours, and whether a structure is on the National Highway System (NHS) or a corridor of statewide significance. The CF is based on a Health Index (HI) currently under development, but which synthesizes data on bridge deck, superstructure, and substructure condition. The SCF consists of a weight reduction factor that measures how well a structure can sustain different types of loading, *waterway adequacy*, and deck width. Lastly, the CEF is calculated by finding the ratio of the action cost (amount of funding required for a project) to the bridge replacement cost.

Table 3.6 Virginia DOT Bridge Prioritization Factors

Factor	What It Measures	Weighting
Importance Factor (IF)	• Relative importance of bridge within a highway network	30%
Condition Factor (CF)	• Overall physical condition of bridge based on the condition of each element	25%
Design Redundancy Factor (DRF)	• Fracture Critical (redundancy), Scour Susceptibility, Fatigue, Earthquake Vulnerability	15%
Structure Capacity Factor (SCF)	• A structure's capacity to convey traffic, including the effects of weight restrictions, vertical clearance, and deck width	10%
Cost-Effectiveness Factor (CEF)	• Cost-effectiveness of the required work	20%

3.2.4 Colorado

Colorado DOT's (CDOT) bridge program consists of two entities, a statewide headquarters branch (Staff Bridge) and the Colorado Bridge Enterprise (CBE), a dedicated program focused on replacing structures that rate poorly (CDOT n.d.). The agency divides potential actions into four treatment types: preventative, repair/rehabilitative, safety treatments, replacement. Two mechanisms are used to identify and prioritize bridge projects: the Structure Preservation Program (SPS) and CBE process. To recommend actions within each of CDOT's regions, Staff Bridge calculates a risk-based Total Priority Score using model-based data analytics (MODA). This score synthesizes data on structure condition, mobility, safety, economics, deck seals and expansion joints, and channel/scour scores. Eq. 4 is used to compute the Total Priority Score.

$$\text{Total Priority Score} = (\text{BPM Score} + \text{Scour Priority Score}) \times \text{CPF} \qquad \text{(Eq. 4)}$$

The Combined Prioritization Factor (CPF) incorporates data on structure condition, mobility, safety, and economic scores. The Bridge Preventative Maintenance Score (BPM) is derived by taking the CPF and adding scores for bridge deck seals and expansion joints. A similar method is used to calculate the Scour Priority Score, where data on channel condition and scour are combined with the CPF. The underlying logic is that separating the BPM from the Scour Priority Score lets CDOT independently examine project priorities. Higher scoring structures receive higher priority.

Each bridge receives a Total Priority Score, with funding distributed among regions based on the sum of priority scores in the region.

CBE project selection leverages the MODA-based framework to prioritize and rank structures needing replacement. During prioritization, CBE considers quantitative and qualitative factors. Quantitative data pertain to structure condition while qualitative data encompass safety issues, regional priorities, and asset bundling opportunities identified by Staff Bridge and region staff. Quantitative and qualitative data for each structure are converted to weighted numerical values, which then inform prioritization. Project programming hinges on resource availability. Historically, CDOT has eschewed life cycle cost (LCC) analysis to select bridge preservation or replacement actions. However, this analysis is now used to determine the total LCC per service year needed to preserve a structure for its 75-year design life and identify preservation actions that will most reduce LCC per service year by delaying replacement to the latest possible date.

3.2.5 Massachusetts

Massachusetts DOT's (MassDOT) Bridge Program covers all bridges the agency is responsible for inspecting (see Pollack et al. 2015). Three criteria are used in the bridge prioritization system to evaluate the relationship between a facility's condition and the risk posed to the transportation network by that condition: (1) Condition Loss (CL), based on the NBIS Condition Rating System; (2) Change in Health Index (HI), a composite measure representing the condition of each bridge element that provides an estimate of a bridge's deterioration rate; and (3) Highway Evaluation Factor, a composite measure of asset criticality computed using five factors: (a) roadway classification, (b) detour length, (c) ADT, (d) load carrying restrictions, and (e) deck geometry deficiency. These measures are synthesized using Eq. 5 to assign each bridge a priority ranking.

$$\text{Rank Value} = 3(\text{CL}) + .4(\text{HI}) + .3(\text{HEF}) \qquad \text{(Eq. 5)}$$

As scores increase, priority level increases. Priority bridges are selected to maintain similar average health indices across MassDOT's six highway districts. In addition to rankings generated through Eq. 5, input from district offices guides decisions about bridge projects because district-level staff have better insights into factors which are not explicitly incorporated into the formula (e.g., high maintenance costs, critical destinations near a bridge, safety concerns). Bridges are selected for rehabilitation, reconstruction, or replacement using this approach, and as projects move through the design process, staff identify improvements pursuant to MassDOT policies.

3.2.6 Ohio

Ohio DOT's (ODOT) Local Major Bridge Program uses a scoring system to appraise the merits of bridge projects (ODOT 2020). The program covers bridges with deck areas > 35,000 square feet which carry vehicle traffic. A criteria-based selection process scores proposed projects in four categories — General Appraisal, Local Share, Economic Health, Regional Impact (Table 3.7). During initial scoring, the maximum number of points for each category is 10. Initial scores are then multiplied by category-specific weighting factors ranging from 1.0 to 3.5. ODOT regards General Appraisal as the most important factor, so it receives the highest weight of 3.5. Following reweighting, scores across categories are summed. The maximum number of points a project can earn is 100.

General Appraisal is a composite measure of key structural elements (beams, piers, abutments). Scoring is done relative to the as-built condition, and each facility is rated on a scale from 0 to 9, with points only awarded for scores ≤ 4. Local Share reflects how willing a bridge owner is to procure funding from entities beyond ODOT. It is measured in both nominal dollars and as a percent contribution. Economic Health measures the economic stress tied to the unemployment rate in the project sponsor's jurisdiction. This measure is included to foster equity, with more points awarded for higher unemployment rates. Regional Impact equally weights ADT and functional class.

Table 3.7 Scoring Criteria for the Ohio DOT Local Major Bridge Program

Category	Maximum Points	Weight Factor	Total Points
General Appraisal	10	3.5	35
Local Share			

Category	Maximum Points	Weight Factor	Total Points
• Percent • Amount	• 10 • 10	• 1.0 • 1.0	• 10 • 10
Economic Health	10	1.5	15
Regional Impact • ADT • Functional Class	10 • 5 • 5	3.0	30

The prioritization system facilitates project rankings, however, the results from this process are not binding as the Local Major Bridge Program Manager ultimately selects projects based on merit and available funding. Projects do not have to be funded in the order they are ranked, and the Program can consider other factors when deciding on funding (e.g., delivery performance on past projects, funding previously awarded, available MPO funds).

Fereshtehnejad et al. (2017) in a study funded by ODOT proposed developing an Ohio Bridge Condition Index (OBCI) capable of evaluating maintenance, rehabilitation, and replacement actions across multiple scales. It examines implementation costs (the amount to repair or upgrade a structure, including user costs) as well as structural and serviceability failure costs (cost and consequences of existing bridge condition) to help decision makers identify an appropriate course of action. The OBCI evaluates bridges at four scales — element, component (groups of different elements which operate together to impact the structural integrity or serviceability of a bridge), bridge, and network. Networks can be examined at multiple levels (e.g., by region, district, county, or the entire state). The index consists of two models: OBCI_{min} and $\text{OBCI}_{\text{current}}$. The first model uses data on minimum performance thresholds to define unacceptable conditions for bridge elements. Based on knowledge of acceptable levels of safety and serviceability, OBCI_{min} is calculated using Eq. 6.

$$\text{OBCI}_{\text{min}} = 1 - \frac{\sum \text{Cost of Meeting Minimum Thresholds}}{\text{Replacement Cost}} \qquad \text{(Eq. 6)}$$

Replacement cost is the cost of replacing the system. Eq. 6 is a high-level representation of OBCI_{min} and does not capture the groups of nested equations deployed at the different scales to determine where a system lies relative to minimum performance thresholds (see Fereshtehnejad et al. 2017, pp. 154–155). The second model, $\text{OBCI}_{\text{current}}$, conceptualizes system performance in terms how much it will cost to return a system to like-new condition (Eq. 7).

$$\text{OBCI}_{\text{current}} = 1 - \frac{\sum \text{Cost of Going Back to Like New Condition}}{\text{Replacement Cost}} \qquad \text{(Eq. 7)}$$

As the cost of achieving like-new condition near the replacement cost, $\text{OBCI}_{\text{current}}$ approaches zero. Scores closer to one indicate better bridge health.

3.2.7 Iowa

Iowa DOT (IDOT) commissioned a study to review asset management practices for bridges (Neubauer 2017). A primary goal of this study was to evaluate the utility of a new software package for predicting future investment priorities. The first step was to subdivide the agency’s bridge inventory into uniform groups of structures with similar deterioration characteristics (e.g., continuous steel girders on mainline interstates, continuous slabs on non-interstate highways). This yielded 13 bridge classes. Next, nine physical and operational factors that influence deterioration were identified from NBI data — age, ADT, ADTT, length of maximum span, number of lanes on bridge, deck protection (wearing surface), deck protection (reinforcing steel), design load, and skew angle. To understand how risk impacts bridge criticality, the study identified and applied weights to five factors (Table 3.8). Higher scores on each criticality index correspond to higher impacts — a score of 1 indicates insignificant impacts while a score of 3 denotes severe impact.

Table 3.8 Iowa Bridge Weightings

Criticality Factor	Weight (%)	Criticality Index
Highway System	25	• Non-NHS — 1 • NHA — 3
Functional Class	30	• Rural Minor Arterial/Collector/Local — 1 • Urban Collector/Local/Rural Arterial — 2 • Urban Arterial — 3
Detour length	15	• ≤ 10 miles — 1 • 10 – 30 miles — 2 • > 30 miles — 3
Type of Service Under Bridge	5	• Waterway — 1 • Pedestrian/Railroad (RR)/RR-Waterway — 2 • Highway/Highway-RR/Highway-Waterway/Highway-Waterway-RR — 3
ADT	25	• < 4,000 — 1 • 4,000 – 10,000 — 2 • > 10,000 —3

The Criticality Index gauges how urgently an intervention is needed. NBI condition rating was factored into a risk index for establishing work priorities. Lastly, the study identified feasible actions to replace, repair, or rehabilitate bridges, resulting in six preservation methods under 16 scenarios. The project's second phase adopted IDOT's Bridge Condition Index (BCI) as a prioritization tool, which accounts for risk, structure condition, and structure criticality; it also investigated different budget scenarios to determine their impact on inventory condition.

3.2.8 Connecticut

Connecticut DOT's (CTDOT) Local Bridge Program provides financial assistance to municipalities to pay for the removal, replacement, reconstruction, or rehabilitation of local bridges. Its prioritization rankings make significant use of NBI data (CTDOT 2019). Individual bridges receive a priority rating; structures with the lowest priority ratings are those in the worst condition. Priority ratings for structures with abutments and piers are calculated using Eq. 7 (a separate equation is applied to culverts and arches). It integrates Sufficiency Rating, which is a single numerical value that synthesizes data on structural adequacy and safety, serviceability and functional obsolescence, and essentiality for public use (see the NBI Coding Guide for calculation methods). Scores range between 0% (total deficient) to 100% (entirely sufficient).

$$\text{Priority Rating} = \text{SR} - 2\left(1 - \frac{\text{DC+SUB+SUP}}{27}\right) - 4\left(1 - \frac{\text{IR}}{36}\right) \qquad \text{(Eq. 7)}$$

where:
SR = Sufficiency Rating
DC = Deck Condition Rating (0-9)
SUB = Condition Rating of Substructure (0-9)
SUP = Condition Rating of Superstructure (0-9)
IR = HS-20 Gross Inventory Rating in Tons

The primary factor used in assessment is physical condition, although other variables are considered (e.g., ADT, detour length, waterway adequacy). Each year the Local Bridge Program publishes a list of bridges eligible for project funding based on the most recent inspection data. Eligible bridges are those which are (1) deficient and (2) meet eligibility criteria of the funding programs.

3.2.9 Texas

Texas DOT's (TxDOT) Highway Bridge Program (HBP) follows a simple approach to prioritize bridge projects (TxDOT n.d.). To be eligible for funding under the HBP, a bridge must have (1) have a Sufficiency Rating (SR) ≤ 80 and (2) be classified as Structurally Deficient or Functionally Obsolete. If a bridge meets the second benchmark and has a SR ≤ 80 it is eligible for rehabilitation, whereas structures with a SR ≤ 50 are eligible for replacement. In some cases, a bridge with a SR > 50 may be replaced if doing so is economically justified. Once bridges are inspected and scored, they are ranked based on their SRs — bridges with the lowest ratings garner the highest priority. This process results in a list of eligible structures that is distributed to TxDOT district offices. District staff consult with local officials to generate a list of proposed projects. Included on this list are special consideration projects not selected during the initial screening. An example of a special consideration is a bridge which serves as the only route to a school or hospital. After TxDOT's Bridge Division receives district-level project lists, it compiles a statewide list of projects. Projects on this list are programmed until funding for the fiscal year runs out.

3.2.10 California

The California Department of Transportation (Caltrans) developed the Bridge Health Index (BHI), which is housed in the AASHTO Pontis bridge management system. The BHI takes a weighted average of element conditions and uses failure costs, repair costs, or other agency-determined weights to assess bridge condition (Shepard and Johnson 2001). Each component is usually given a rating of 1 – 100. The BHI is computed in two steps. First, each element is assigned an element health index (EHI) score. The EHI scores are then aggregated to estimate the BHI. The BHI is used to identify which bridges should be repaired, replaced, or are in satisfactory condition. For the BHI to work it must satisfy three conditions. First, it must be able to determine the current health of bridge elements. Second, there must be a way to accurately predict future conditions and efficiently model bridge deterioration. Lastly, feasible options for maintenance, repair, or replacement should be available (Inkoom and Sobanjo 2019). Using element-level inspection data, a thorough assessment can be undertaken, comparisons made, and resources allocated across bridges. Of course, the BHI approach has limitations such as lacking element-level data and not accounting for capacity, ADT, scour, and fatigue (Chase et al. 2016).

California has transitioned to the BHI because it enables more analytical decisions on bridge maintenance: "A bridge health or condition index is used as a performance measure by agencies interested in preserving the condition of bridge structures or prioritizing the maintenance or replacement projects within their bridge inventory" (Chase et al., p. 1). Limitations of the approach include the lack of economic value calculations and infeasibility of accurately calculating future element conditions. The BHI also fails to consider a bridge's economic value. Recent assessments of the weighting have resulted in an attempt to develop importance weights for elements (Inkoom et al. 2017).

3.2.11 Kentucky

Peiris and Harik (2018) devised a two-level prioritization system for Kentucky's historic steel truss bridges to inform decisions about rehabilitation or preservation. The first level is the Historical Importance Factor (HIF), which accounts for truss uniqueness (x_1), bridge age (x_2), unique features of bridge construction (x_3), and a bridge's historic features (x_4). Each factor is scored according to a series of rules laid out in the report (see pp. 4–7 in Peiris and Harik [2018]). For example, with truss uniqueness a bridge garners a higher score when it shares a truss type with a small number of other bridges. If a bridge shares its truss type with just one other bridge in the state it receives a score of 8 for x_1; conversely, if the truss type is more common, fewer points are awarded, down to 1 if four or more bridges have truss types similar to the bridge under consideration. Once factors are scored, they are multiplied together (Eq. 8). Unlike some other systems, this one leans on multiplication — rather than summation — because it is more likely to detect historically important bridges.

$$\mathrm{HIF} = x_1 x_2 x_3 x_4 \quad \text{(Eq. 8)}$$

When multiple bridges receive the same HIF score, a second-level prioritization factor is used to order rehabilitation priorities. This factor — designated P2F — is based on a Bridge Condition Factor (BCF), Rehabilitation Potential Factor (RPF), or both. The BCF is calculated using data on structural condition and channel state (NBI Items 58 – 61), while the RPF gauges how well a proposed rehabilitation can address three factors — a capacity factor, a geometric factor, and a safety factor.

3.3 Key Takeaways

- There are three main types of bridge indices or approaches to managing bridge systems: Bridge Condition Rating, Bridge Health Index, and Bridge Importance Index. These systems are used in several states, although other approaches are used as well.
- Many agencies rely on prioritization systems to identify bridge and culverts needing repairs, rehabilitation, or replacement. Typically, the methodological frameworks employed by DOTs make significant use of NBI data — especially items 58–60 (which represent a structure's physical condition) and different metrics that quantify the criticality of assets in broader transportation networks. Data on geomorphic and hydraulic variables are often factored into decision making, however, they tend to receive less weight than information on physical condition and traffic characteristics.
- Rarely do prioritization lists generated through purely objective measures have the final say in what projects are funded. Expert knowledge from agency staff — especially at the local or district level — can be invaluable for understanding context-specific factors that are considered at the programming stage. While indices that attempt to summarize bridge condition and performance in a single metric can point toward system assets in need of attention, they cannot encapsulate on-the-ground knowledge that eludes quantification.

Chapter 4 Kentucky Enhanced Bridge Prioritization Index

4.1 Methodology

We collaborated with a working group of KYTC subject-matter experts to develop an Enhanced Bridge Prioritization Index (EBPI) for Kentucky. Our team of facilitators guided Cabinet stakeholders through the Analytic Hierarchy Process (AHP) to determine the relative importance of each factor that was ultimately included in the EBPI. Vargas (2010) described AHP as "a technique for decision making in complex environments in which many variables or criteria are considered in the prioritization and selection of alternatives or projects." Applications of AHP are abundant (e.g., Saaty 1990, Saaty 1987, Saaty 1994, Saaty 2008, Vaidya and Kumar 2006, Vargas 1990, Vargas 2010, Hummel et al. 2014, Yap et al. 2019). Forman and Gass (2001) observed that AHP can be used for prioritization and other applications.

Saaty (2008, p. 85) identifies AHP's four steps:

- Define the problem and determine the kind of knowledge sought.
- Structure the decision hierarchy from the top with the goal of the decision, then the objectives from a broad perspective, through the intermediate levels (criteria on which subsequent elements depend) to the lowest level (which usually is a set of the alternatives).
- Construct a set of pairwise comparison matrices. Each element in an upper level is used to compare the elements in the level immediately below with respect to it.
- Use the priorities obtained from the comparisons to weigh the priorities in the level immediately below. Do this for every element. Then for each element in the level below add its weighed values and obtain its overall or global priority. Continue this process of weighing and adding until the final priorities of the alternatives in the bottom most level are obtained.

We adopted a modified version of AHP for this project:

- Identify factors to be included in index through facilitated workshops and follow-up surveys
- Group factors based on commonality and assign category labels
- Use individual pairwise comparisons to assign relative importance using the Fundamental Scale for Pairwise Comparisons, or Saaty's Fundamental Scale (Table 4.1)[18]
- Generate a comparison matrix from a group aggregation of pairwise comparisons
- Normalize the matrix by dividing each column entry's value by the total column value
- Each factor's relative contribution to the index is determined by calculating the Eigenvector, which is the sum of the rows in the matrix divided by the number of columns
- The Eigenvector values (Eigenvalues), or independent weightings, for the category labels are multiplied by each group factor's Eigenvector, yielding global priorities where scores range between 0 and 1, with the sum of the global priorities equaling 1
- Check data consistency using Consistency Ratios

Table 4.1 Fundamental Scale

Magnitude of Importance	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective
3	Moderate importance	Experience and judgement moderately favor one factor over another
5	Strong importance	Experience and judgement strongly favor one factor over another

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[18] This approach and table are also cited by FHWA: https://www.fhwa.dot.gov/bridge/abc/dmtool/survey_form.cfm

Magnitude of Importance	Definition	Explanation
7	Very strong importance	One factor is favored very strongly over another and its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one factor over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values	Used when a compromise option is necessary

4.2 Results

After identifying factors to include in the proposed index, the working group placed factors into three categories — Condition, Mobility, and Risk. Those groupings and the factors comprising each are shown in Figure 4.1.

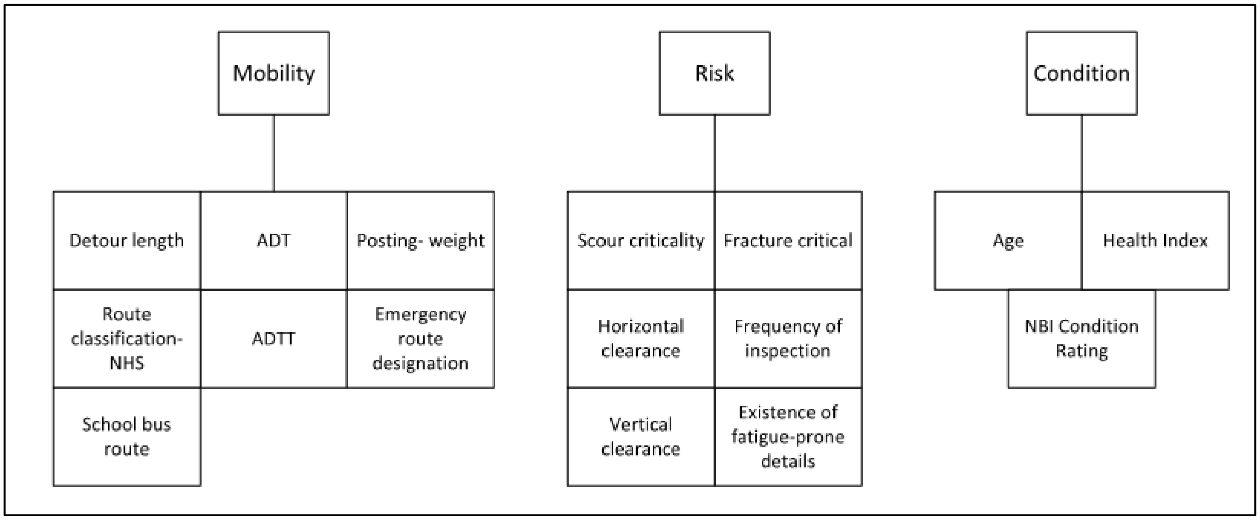

Figure 4.1 Index Factors

Using a pairwise comparisons approach, each factor and category was assigned an independent weight derived from the scoring matrices. As a group decision-making process[19] AHP often follows one of two approaches — (1) Aggregation of Individual Judgements (AIJ) (Saaty 1989) or (2) Aggregation of Individual Priorities (AIP) (Ramanathan and Ganesh 1994, Forman and Peniwati 1998) approaches. We conducted three rounds of rankings to discuss differences in opinions, however, because each subject-matter expert maintained their individual preferences AIP is the most appropriate approach. AIP aggregates individual priorities using either the geometric or arithmetic mean so alternatives can be ranked based on group outcomes (Yap et al. 2019). Forman and Peniwati (1998) noted that "the geometric mean is more consistent with the meaning of both judgements and priorities in AHP" (p. 169). Once aggregated priorities were calculated for categories and factors, category weights were multiplied by the weight for each factor in that category to arrive at its contribution to the overall score, or global priority. For example, the Health Index accounts for 26% of a structure's score. EBPI scores range between 0 and 1, where 0 indicates the lowest priority and 1 the highest priority. Tables 4.2 – 4.4 shows the index's global priorities for Mobility, Risk, and Condition, respectively.

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[19] For a scan of literature on group aggregation techniques see Ossadnik et al. (2016).

Table 4.2 Kentucky Enhanced Bridge Prioritization Index Weights — Mobility

Factor	Contribution to Overall Score
Detour length	0.51%
ADT	2.38%
ADTT	1.64%
Posting-weight	2.92%
School bus route	0.51%
Route classification- NHS	1.01%
Emergency Route Designation	0.53%

Table 4.3 Kentucky Enhanced Bridge Prioritization Index Weights — Risk

Factor	Contribution to Overall Score
Vertical clearance	1.62%
Scour criticality	9.57%
Fracture-critical	3.89%
Horizontal clearance	0.78%
Existence of fatigue-prone details	3.85%
Frequency of inspection	1.77%

Table 4.4 Kentucky Enhanced Bridge Prioritization Index Weights — Condition

Factor	Contribution to Overall Score
Age	5.24%
NBI Condition Rating	37.29%
Health Index	26.49%

Evaluating data inconsistencies is done to ensure those participating in the decision-making process made consistent choices. To measure consistency, a consistency index was calculated using Eq. 9 (e.g. Saaty 1994, Saaty 1987).

$$\text{Consistency Index} = \frac{\text{Max.Eigenvalue} - \text{n}}{\text{n} - 1}; \text{where n} = \text{number of criteria} \qquad \text{(Eq. 9)}$$

The maximum Eigenvalue is the sum of each Eigenvector in a category multiplied by its respective column total. The consistency ratio is calculated with Eq. 10.

$$\text{Consistency Ratio} = \frac{\text{Consistency Index}}{\text{Random Consistency Index}} \qquad \text{(Eq. 10)}$$

The Random Consistency Index (RI) is a function of the number of criteria being evaluated with values in Table 4.5

Table 4.5 Random Consistency Index

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Table 4.6 provides the resulting consistency ratios for each index category along with the category labels.

Table 4.6 Consistency Ratios

Category Label	Consistency Ratio
Risk, Mobility, Condition	2.41%

Category Label	Consistency Ratio
Risk	18.69%
Mobility	8.03%
Condition	0.55%

Saaty (1987) proposed a 10% ratio threshold as acceptable, however < 20% is considered tolerable (Saaty 1980, Apostolou and Hasell 1993, Wedley 1993). For certain factors, particularly those in the Risk category, subject-matter experts expressed consistent disagreement about their relative importance. The aggregation and final rankings reflect their positions, resulting in a slightly higher consistency ratio. A one-page graphic summary was prepared for KYTC to summarize the process and review project results (Appendix B).

4.3 Additional Index Screening

Additional screening criteria were also discussed. As KYTC is responsible for over 14,000 bridges, there may be situations where adding some screening criteria to the results of the index could help identify bridges that — despite having similar rankings to other structures — may need additional scrutiny when there are limited resources. The first screening method is based on vulnerability. This relies on a diagnostic framework developed by Van Dyke et al. (2021) that can be used to identify bridges and culverts that may be susceptible to damage from flooding and scour. At the heart of this framework is a Bridge and Culvert Sensitivity Index (BCSI) and three constitutive indices — (1) Structural Condition Index, (2) Geomorphic Sensitivity Index, and a (3) Criticality Index. This approach leverages NBI data as well as data collected by the Cabinet during routine structure inspections, to identify problematic facilities (Table 4.5). Each index is calculated by rescaling factor scores, multiplying rescaled scores by weighting factors, and then summing the scores (Eq. 11). Each index produces a final score between 1 and 3, where 1 indicates low sensitivity/criticality to flooding and 3 denotes high sensitivity/criticality.

$$\text{Index Score} = \sum_{i=1}^{n} f_i w_i \quad \text{(Eq. 11)}$$

Although the BCSI was originally designed with an emphasis on geomorphic sensitivity, its calculations integrate many data elements found in the prioritization indices and equations used by other state DOTs.

Table 4.7 Bridge and Culvert Sensitivity Index Data Inputs

Index	Data Inputs
Structural Condition	• NBI Items • Deck (58), Superstructure (59), Substructure (60)Culvert (62)
Geomorphic Sensitivity	• NBI Items • Channel and Channel Protection (61), Waterway Adequacy (71), Scour Critical Bridges (113) • KYTC Items • Scour Observed, Scour Risk Calculation
Criticality	• NBI Items • Bypass, Detour Length (19), ADT (29), Structure Length (49), Highway System of Inventory Route (104), Average Daily Truck Traffic (109)

The importance of bridges for freight movement was also considered as a screening option for EBPI results. The value of freight crossing a span is another potentially important consideration, although there is no clear method for easily determining the value of freight that traverses a specific bridge. The Strategic Highway Investment Formula for Tomorrow (SHIFT) incorporates freight economic growth measures to prioritize capital improvement projects. SHIFT includes five attributes: safety, asset management, congestion, economic growth, and benefit-cost. Under economic growth, a freight economic growth measure is included that could be used, but data requirements may restrict its application to a limited subset of bridges. Additional research and data collection are likely necessary to fully operationalize a freight screening tool for bridges.

Chapter 5 Summary and Conclusion

KYTC inspects over 14,000 bridges throughout Kentucky, including 9,000 state-owned bridges. These structures are vital links in the state's transportation network and help move people and freight from their origins to destinations. Historically, the Cabinet has prioritized bridge maintenance projects based on factors such as sufficiency ratings and input from district offices. Sufficiency ratings provide an overall measure of bridge condition on a scale from 1 to 100. A perfect score of 100 indicates a bridge is in excellent condition (and usually new). While sufficiency ratings attend to structural adequacy and safety, design obsolescence, and asset importance, they omit key information that can inform prioritization, especially when funding is insufficient to address all needs.

To improve bridge prioritization practices and aid decision makers, our team collaborated with KYTC subject-matter experts to develop developed the Enhanced Bridge Prioritization Index (EBPI). Cabinet stakeholders identified the index components and ranked them during several brainstorming sessions. EBPI values are calculated based on data for 16 factors, which are grouped into three categories — **Condition, Mobility, and Risk**. Weights are assigned to each factor. Because the sum of these weights equals 1, EBPI scores range between 0 and 1, where 0 indicates the lowest priority and 1 the highest priority. Additional screening criteria can be operationalized when the scores for several bridges are clustered together. When funding is limited, using these additional criteria could help decision makers identify bridge(s) to address during the current budget cycle.

Applying the EBPI methodology to analyze other transportation assets (e.g., pavements) would improve cross-asset comparisons. Because the EBPI will be used to rank projects over the next several budget cycles, KYTC will have the opportunity to review its performance and update it as needed.

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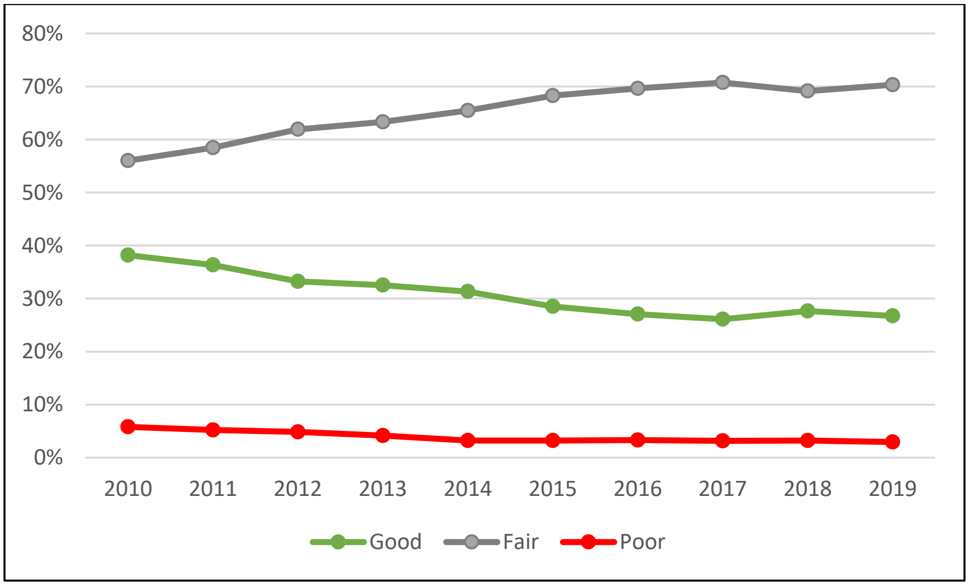
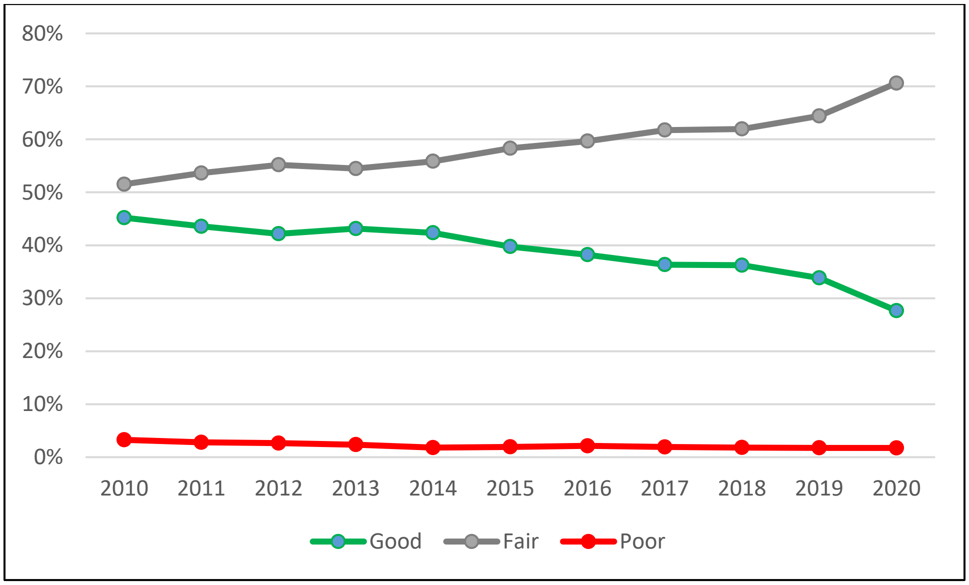
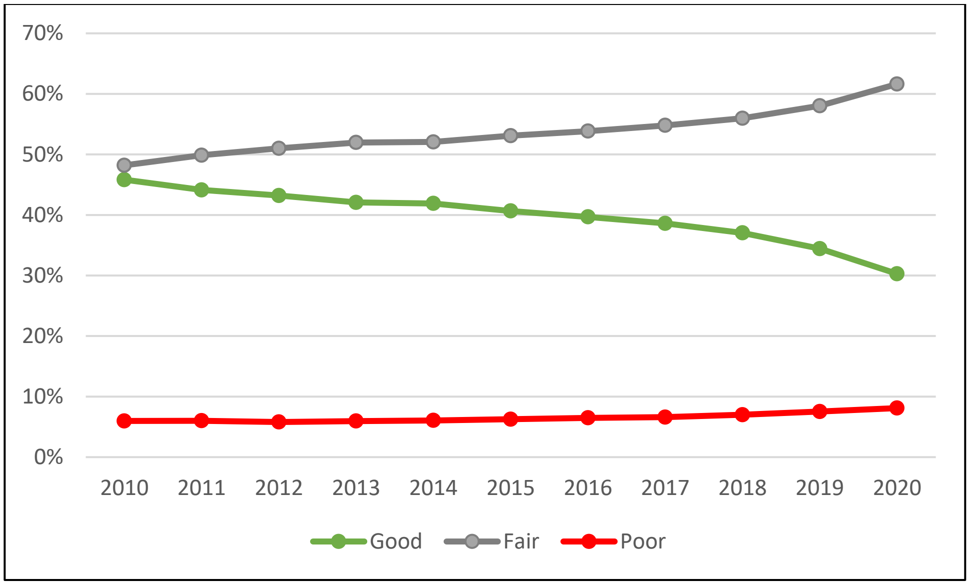
Appendix A Bridge Condition Data



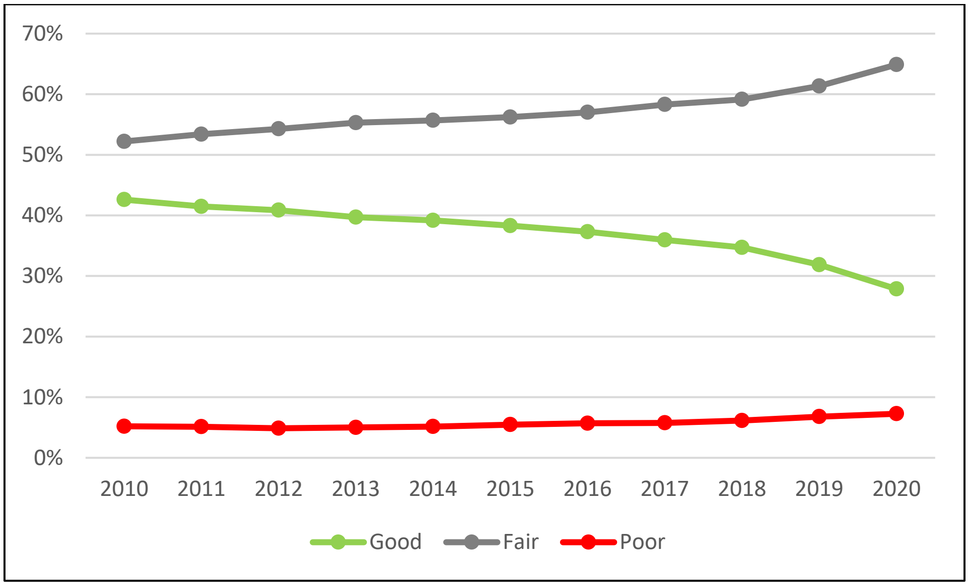
Kentucky Interstate Bridges Condition



Kentucky NHS Bridges Condition

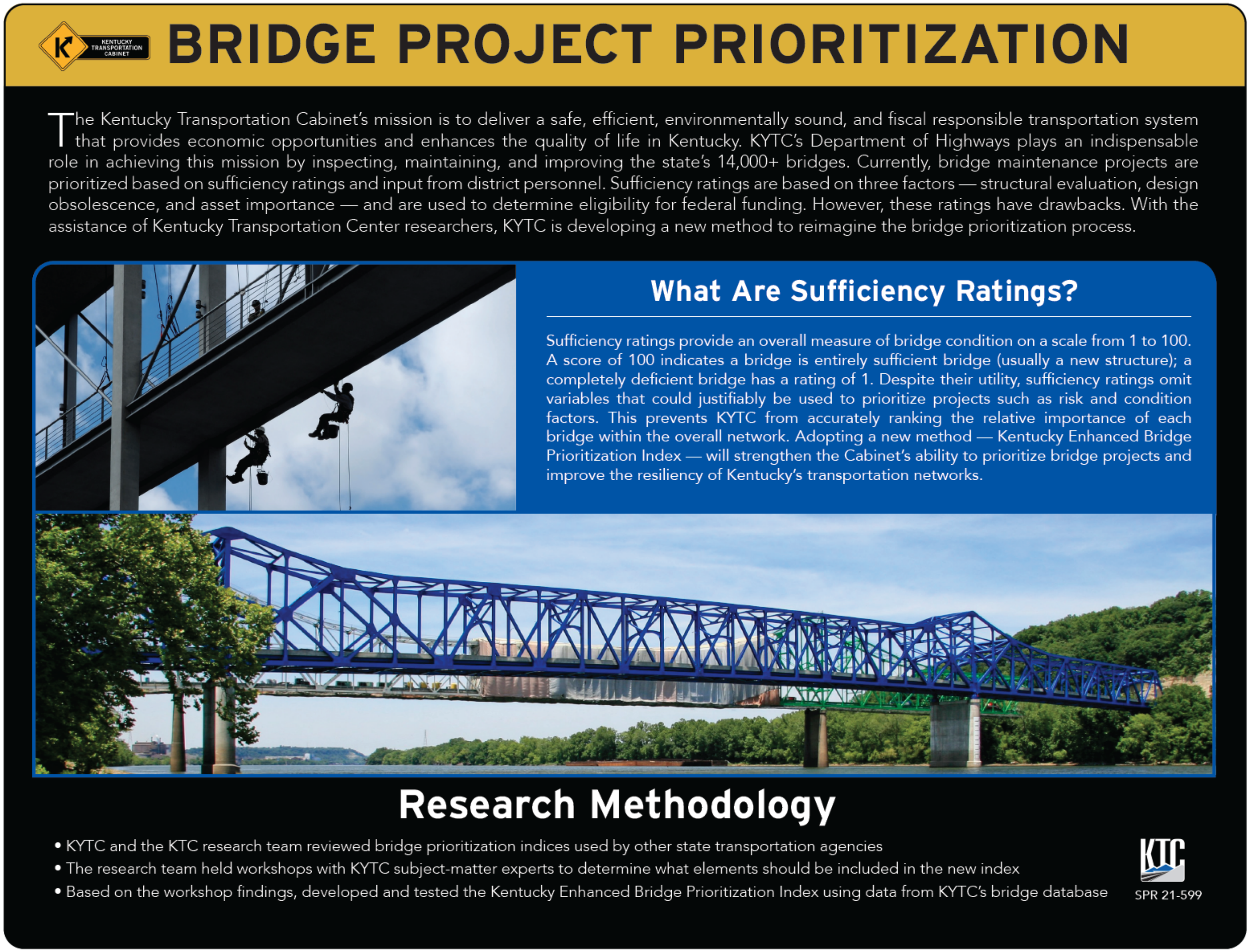


All Kentucky Non-NHS Bridges Condition



State-owned Non-NHS Bridges Condition

Appendix B Project Summary



BRIDGE PROJECT PRIORITIZATION

The Kentucky Transportation Cabinet's mission is to deliver a safe, efficient, environmentally sound, and fiscal responsible transportation system that provides economic opportunities and enhances the quality of life in Kentucky. KYTC's Department of Highways plays an indispensable role in achieving this mission by inspecting, maintaining, and improving the state's 14,000+ bridges. Currently, bridge maintenance projects are prioritized based on sufficiency ratings and input from district personnel. Sufficiency ratings are based on three factors — structural evaluation, design obsolescence, and asset importance — and are used to determine eligibility for federal funding. However, these ratings have drawbacks. With the assistance of Kentucky Transportation Center researchers, KYTC is developing a new method to reimagine the bridge prioritization process.

What Are Sufficiency Ratings?

Sufficiency ratings provide an overall measure of bridge condition on a scale from 1 to 100. A score of 100 indicates a bridge is entirely sufficient bridge (usually a new structure); a completely deficient bridge has a rating of 1. Despite their utility, sufficiency ratings omit variables that could justifiably be used to prioritize projects such as risk and condition factors. This prevents KYTC from accurately ranking the relative importance of each bridge within the overall network. Adopting a new method — Kentucky Enhanced Bridge Prioritization Index — will strengthen the Cabinet's ability to prioritize bridge projects and improve the resiliency of Kentucky's transportation networks.

Research Methodology

- KYTC and the KTC research team reviewed bridge prioritization indices used by other state transportation agencies
- The research team held workshops with KYTC subject-matter experts to determine what elements should be included in the new index
- Based on the workshop findings, developed and tested the Kentucky Enhanced Bridge Prioritization Index using data from KYTC's bridge database

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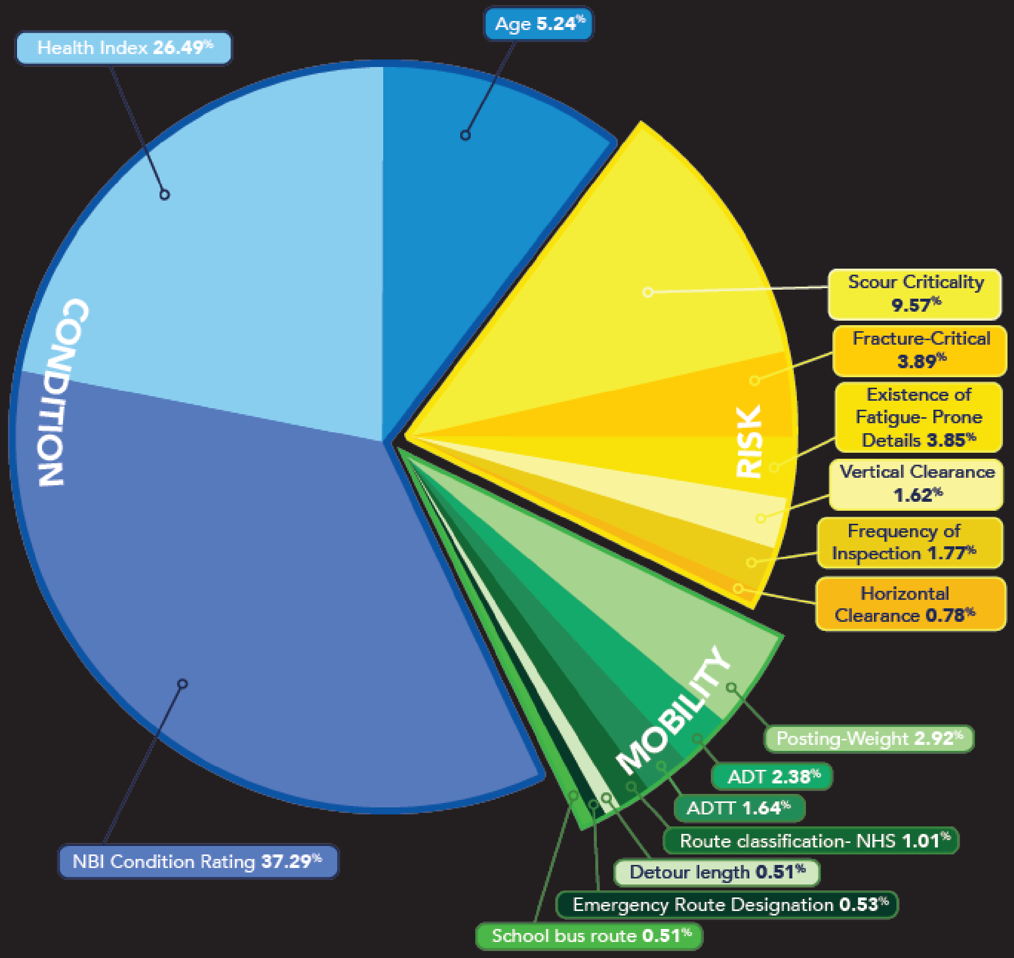
Kentucky Enhanced Bridge Prioritization Index



Facilitated by KTC researchers, the Cabinet's subject-matter experts followed the Analytic Hierarchy Process to determine the relative importance of each factor included in the Enhanced Bridge Prioritization Index. Factors are grouped into three categories — **Condition, Mobility, and Risk**. Each factor is assigned a weight that denotes its contribution to the overall score. For example, the Health Index accounts for 20% of a structure's score. The pie chart and the table capture the weights assigned to each factor. Enhanced Bridge Prioritization Index scores range between 0 and 1, where 0 indicates the lowest priority and 1 the highest priority.

Condition	
Age	5.24%
NBI Condition Rating	37.29%
Health Index	26.49%
Risk	
Vertical Clearance	1.62%
Scour Criticality	9.57%
Fracture-Critical	3.89%
Horizontal Clearance	0.78%
Existence of Fatigue-Prone Details	3.85%
Frequency of Inspection	1.77%
Mobility	
Detour length	0.51%
ADT	2.38%
ADTT	1.64%
Posting-weight	2.92%
School bus route	0.51%
Route classification- NHS	1.01%
Emergency Route Designation	0.53%

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