How Pavement and Bridge Conditions Affect Transportation System Performance

With Example Transportation Asset Management Plan Chapters Supporting System Performance Objectives

FHWA-HOP-22-077

FEDERAL HIGHWAY ADMINISTRATION

Office of Operations

1200 New Jersey Avenue, SE

Washington, DC 20590

U.S. Department of Transportation
Federal Highway Administration

October 2023

Technical Report Documentation Page

<table>
<tr><td>1. Report No.
FHWA-HOP-22-077</td><td>2. Government Accession No.</td><td colspan="2">3. Recipient's Catalog No.</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle
How Pavement and Bridge Conditions Affect Transportation System Performance</td><td colspan="2">5. Report Date
October 2023</td></tr>
<tr><td colspan="2">6. Performing Organization Code
None.</td></tr>
<tr><td colspan="2">7. Author(s)
Gordon Proctor, Shobna Varma, and Dr. Omar Smadi, PhD.</td><td colspan="2">8. Performing Organization Report
None.</td></tr>
<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address
Gordon Proctor & Associates
7825 Wiltshire Drive
Dublin, OH 43016
Starisis Corporation
3737 Woodstone Drive
Lewis Center, OH 43035
Center for Transportation Research and Education
Iowa State University
2711 Loop Drive
Ames, IA 50010</td><td colspan="2">10. Work Unit No.
None.</td></tr>
<tr><td colspan="2">11. Contract or Grant No.
693JJ319D000020</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Agency Name and Address
Federal Highway Administration
Office of Operations
1200 New Jersey Avenue, SE
Washington, DC, 20590</td><td colspan="2">13. Type of Report and Period Covered:
Final Report</td></tr>
<tr><td colspan="2">14. Sponsoring Agency Code
FHWA</td></tr>
<tr><td colspan="4">15. Supplementary Notes:
Federal Highway Administration Office of Operations
Task Order Contracting Officer’s Representative (TOCOR)—Joseph Gregory</td></tr>
<tr><td colspan="4">16. Abstract
This document takes an expansive view and considers how pavement and bridge conditions can contribute to system performance areas, such as highway safety, freight mobility, or reliability. The document also considers other impacts, such as how attributes such as pavement shoulders, pavement friction, or bridge conditions contribute to highway safety, freight movement, noise reduction, and transportation system resilience. This document also includes three fictional transportation asset management plan (TAMP) chapters illustrating how the TAMP could directly support multiple transportation performance objectives. Those chapters are the performance gap analysis, risk assessment, and investment strategies.</td></tr>
<tr><td colspan="2">17. Key Words
Transportation asset management, transportation performance management, asset conditions, bridge and pavement conditions, system performance, state of good repair, resilience, highway safety</td><td colspan="2">18. Distribution Statement:
No restrictions</td></tr>
<tr><td>19. Security Classification. (of this report) Unclassified</td><td>20. Security Classification. (of this page) Unclassified</td><td>21. No. of Pages
114</td><td>22. Price N/A</td></tr>
</table>

Form DOT F 1700 (8-72) **Reproduction of completed page authorized**

Contents

List of Figures

List of Tables

List of Acronyms

AADT	Annual Average Daily Traffic
ACI	Asset Condition Index
ARC	Atlanta Regional Commission
ATMS	advanced traffic management system
BMP	best management practice
Caltrans	California Department of Transportation
CDOT	Colorado Department of Transportation
CFR	Code of Federal Regulations
CMF	crash modification factor
DOT	department of transportation
DRCOG	Denver Regional Council of Governments
FAF4	Freight Analysis Framework
FHWA	Federal Highway Administration
HMA	Hot mix asphalt
HRRR	High Risk Rural Road
HSIP	Highway Safety Improvement Program
IRI	International Roughness Index
ITS	intelligent transportation system
JPCP	jointed portland concrete pavement
KYTC	Kentucky Transportation Cabinet
LCP	lifecycle planning
LRSTP	Long-Range Statewide Transportation Plan
LTPPP	Long-Term Pavement Performance Program

MEPDG	Mechanistic-Empirical Pavement Design Guide
MnDOT	Minnesota Department of Transportation
MOT SHA	Maryland State Highway Administration
MTP	Metropolitan Transportation Plan
NBI	National Bridge Inventory
NBIS	National Bridge Inspection Standards
NCHRP	National Cooperative Highway Research Program
NFSP	National Freight Strategic Plan
NHFN	National Highway Freight Network
NHS	National Highway System
NZTA	New Zealand Transportation Authority
OGFC	open-graded friction course
OMT	Office of Materials Technology
PSI	Pavement Serviceability Index
RD	rut depth
ROR	run off the road (as in crashes)
SHSP	Strategic Highway Safety Plan
SN	skid number
SOGR	State of Good Repair
TAMP	transportation asset management plan
TSMO	Transportation Systems Management and Operations
TxDOT	Texas Department of Transportation
UDOT	Utah Department of Transportation
USDOT	U.S. Department of Transportation

UTBWC	ultra-thin bonded wearing course
WHO	World Health Organization
WSDOT	Wisconsin Department of Transportation

EXECUTIVE SUMMARY

State Departments of Transportation (DOTs) strive to balance multiple objectives. With limited resources, they try to keep pavements and bridges in good repair, reduce crashes, alleviate congestion, improve travel-time reliability, increase resilience, protect the environment, and contribute to livable communities.

This report examines how those objectives do not occur independent of one another. As State DOTs maintain bridges and pavements in good repair, they also can contribute to crash reduction, increased resilience, improved travel-time reliability, and many other performance objectives. These performance areas may have separate metrics, but they have common linkages. For example, a pavement in good repair may have adequate friction and shoulders that can reduce crashes. Well-maintained bridges can contribute to the efficient movement of freight by allowing permitted super-loads to traverse a region. Robust bridges, culverts, and drainage structures contribute to resilience during extreme weather events so that roadway pavements are not washed out during storms.

This report notes that when asset condition gaps are closed, system performance gaps often are reduced. It describes linkages between pavements and bridges in a state of good repair (SOGR) and achievement of other transportation performance objectives. It summarizes issues such as how:

- The SOGR of pavements and bridges supports transportation system performance objectives, primarily safety, freight reliability, resilience, and other transportation system performance objectives.
- The transportation asset management plan (TAMP) requirements developed under 23 Code of Federal Regulations (CFR) Part 515 support multiple performance plan areas and do not only focus upon achieving National Highway System (NHS) pavement and bridge objectives.
- Each TAMP section can reference its contribution to other performance plans, such as the Strategic Highway Safety Plan (SHSP)[1] or the State Freight Plan[2].

Increasingly relevant in today’s performance environment is the specificity about how pavement and bridge conditions support multiple transportation system performance objectives. Research indicates what thresholds of pavement and bridge conditions influence safety, mobility, reliability, sustainability, resilience, and other performance objectives. For example, research:

- Quantifies the correlation between pavement rutting and crash rates
- Indicates how International Roughness Index (IRI) levels influence crashes
- Explains the links between pavement friction and safety or condition and noise levels
- Links the condition of shoulders to crash rates and the condition of roadway drainage to water quality
- Shows how bridge conditions can influence freight mobility and transportation system resilience

TAMP updates provide opportunities to consider how investments in the SOGR support multiple performance objectives. Updates of TAMPs and other performance plans and programs provide

State DOTs opportunities to evaluate tradeoffs and identify synergies between condition and performance. These plans and programs include the TAMP, the SHSP, the Highway Safety Improvement Program (HSIP), and the State Freight Plan. Also, the long-range statewide transportation plan (LRSTP) and the Metropolitan Transportation Plans (MTPs) provide additional opportunities for coordination.

How to balance investments to enhance condition and multiple transportation objectives is not always clear. For example, a DOT may apply a pavement preservation treatment to extend a pavement's life. However, research indicated that in some cases, pavement preservation treatments decreased pavement friction, which could increase the probability of crashes. Research shows that mixes that can make a pavement quiet may not always make it long lasting. The most economical urban pavement treatment may not support Active Transportation or Complete Streets.[3,4] As plans are developed, stakeholders can be consulted, data can be reviewed, objectives can be evaluated, and trade-offs can be made. The risk-based TAMP development process can assess threats to condition and performance and opportunities to enhance both. Coordination between performance plans and programs could identify opportunities to pool resources, combine projects, or identify shared objectives. The links between condition objectives and performance objectives could be better reflected in projects and investment strategies. By capitalizing on today's unparalleled access to data and research, State DOTs can simultaneously enhance asset conditions and system performance.

What This Document Includes

This document includes 10 chapters that examine issues, such as how TAMPs can:

- Link to other performance plans, such as the SHSP
- Support safety through comprehensive pavement management processes
- Manage bridges to achieve multiple performance objectives
- Increase transportation system resilience through sound bridge and pavement management
- Enhance drainage assets to withstand extreme storm events
- Document the lack of research on how the SOGR supports mobility, operations, or travel-time reliability
- Consider pavement and bridge contributions to Complete Streets and Active Transportation
- View performance plan updates as opportunities for cross-asset and cross-program collaboration
- Summarize how assets in good repair support comprehensive performance management

CHAPTER 1. LINKING THE TAMP TO SYSTEM PERFORMANCE OBJECTIVES

As States' asset management processes further mature, they are likely to strengthen the linkages between asset conditions and system performance. TAMPs are likely to increasingly emphasize the connection between the SOGR and safety, mobility, and reliability. Some linkages between asset conditions and performance include:

- Safety improves when pavement friction is good, ruts are minimal, and shoulders reflect a section's safety needs.
- Quiet pavements can reduce noise and improve a neighborhood's quality of life, which allows pavement strategies to support community objectives stated in the MTP or LRSTP.[1]
- Smooth pavements can reduce fuel consumption and vehicle operating costs.
- Freight movement improves when bridges are not load limited.
- Roads can be more resilient when bridges, pavements, and other assets can withstand increased storm events, increased precipitation, pavement flooding, and rising sea levels.
- Bridges, roads, and streets can be managed to support Active Transportation[2] if the State DOT wants its TAMP to explicitly support such objectives.
- Roadways and their drainage assets can support improved water quality if the state DOT wants to link its investment strategies directly to environmental objectives.

Although the asset management rule in 23 CFR Part 515 requires TAMPs to only include NHS pavements and bridges,[3] many State DOTs are extending asset management efforts beyond those minimums. Twenty-two States included all State-managed routes in the 2019 TAMPs. Also, several States included other assets such as intelligent transportation systems (ITSs), culverts, drainage assets, signs and signals, and even buildings.[4]

The emphasis on NHS performance, as well as on asset conditions, is emphasized in the TAMP requirements stated in 23 CFR Part 515. It states, in part, "A State shall develop a risk-based asset management plan that describes how the NHS will be managed to achieve system performance effectiveness and State DOT targets for asset condition, while managing the risks, in a financially responsible manner, at a minimum practicable cost over the life cycle of its assets."[5]

Also included in 23 CFR Part 515 is, "A State DOT shall develop and implement an asset management plan to improve or preserve the condition of the assets and improve the performance of the NHS."[6]

Definitions in 23 CFR Part 515 also emphasize performance, as well as condition. Performance of the NHS is defined as, "the effectiveness of the NHS in providing for the safe and efficient movement of people and goods where that performance can be affected by physical assets. This term does not include the performance measures established for performance of the Interstate System and performance of the NHS (excluding the Interstate System) under 23 U.S.C. 150 (c)(3)(ii)(A)(IV)-(V)."[7] The Federal Highway Administration (FHWA) defines performance gaps as "the gaps between the current asset condition and State DOT targets for asset condition, and the gaps in system performance effectiveness that are best addressed by improving the physical assets."[8]

Another reason for State TAMPs to strengthen linkages between asset condition and performance comes as State DOTs use their TAMP to support their agency's mission. TAMPs must include objectives that "should align with the State DOT's mission."[9] Improving the "quality of life" is a common element in many State DOTs' mission statements.[10,11,12] One typical example is from the Illinois Department of Transportation, whose mission statement includes, "It is our mission to provide safe, cost-effective transportation for Illinois in ways that enhance the quality of life, promote economic prosperity, and demonstrate respect for our environment."[13]Another is from the Connecticut Department of Transportation, which states, "The mission of the Connecticut Department of Transportation is to provide a safe and efficient intermodal transportation network that improves the quality of life and promotes economic vitality for the State and the region."[14]

If a State DOT chooses, it can expand its TAMP's focus to include more than the minimum requirements of only including NHS pavement and bridge assets. [15]In addition to NHS bridge and pavement assets, "State DOTs are encouraged, but not required, to include all other NHS infrastructure assets within the right-of-way corridor and assets on other public roads. Examples of other NHS infrastructure assets include tunnels, ancillary structures, and signs. Examples of other public roads include non-NHS Federal-aid highways."[16]

Source: iStock.

Figure 1. Photo. The SOGR can include both pavement condition and the roadway's ability to support multiple modes of transportation.

TAMPs may consider not only the physical condition of assets, but also how assets support performance of multiple transportation objectives, such as Active Transportation. As seen in Figure 1, the definition of the SOGR for a roadway could include whether it supports Active Transportation objectives, as well as bridge and pavement condition targets. States have the option of defining asset performance to include more than only achieving a bridge or pavement condition target.

TAMPs also "shall discuss how the plan's investment strategies collectively would make or support progress toward…. achieving the national goals identified in 23 U.S.C. 150(b)."[17] Those goals include safety, infrastructure condition, congestion reduction, system reliability, freight movement and economic vitality, environmental sustainability, and reduced project-delivery delays.[18]

If a State DOT's TAMP includes more than NHS bridges and pavements, then linkages between assets' condition and performance can expand. Examples include:

- Maintaining sidewalks and bike lanes, as well as roadways, can improve safety and environmental sustainability, and support State and metropolitan Active Transportation objectives.
- Drainage assets in good condition complement environmental sustainability and reliability goals.
- Well-maintained safety barriers, signage, lighting, and pavement markings improve safety performance.

Measures and targets can focus attention on how the condition of assets affects performance in multiple areas. One example could be how the age and condition of ITS assets affect travel time reliability. Another could be whether urban bridges accommodate bicycling and walking. A third could be if urban pavement sections include sidewalks and curb ramps.

Another avenue for expanding consideration of how condition affects performance relates to the TAMP's definition of SOGR. Each State DOT defines its SOGR.[19] A State DOT could adopt a definition of SOGR to include more than achieving an asset condition target. Good repair could include the asset's ability to support multiple objectives. Those could include safety, reliability, environmental sustainability, freight mobility, livable communities, or supporting active transportation.

Further reasons for linking TAMPs to system performance comes from the TAMP's linkage to the statewide and metropolitan planning processes.[20,21,22] As cited later in this report, metropolitan plans often include objectives such as reducing pedestrian crashes and promoting Active Transportation. TAMPs and asset management efforts can contribute to these objectives when pavement and bridge programs are linked to them.

State DOTs could use every TAMP section to strengthen the emphasis of how asset conditions affect system performance. For example, State DOTs could if they chose to:

- Include TAMP objectives stating that bridge and pavement assets will be managed to support safety, resilience, reliability, environmental sustainability, and other priorities

- Assess through measures and targets the extent to which bridge and pavement assets support those other objectives
- Analyze how gaps in conditions such as pavement friction could contribute to safety performance gaps
- Mitigate risks in other performance areas by improving bridge and pavement assets; an example could be including Safety Edges℠ on rural pavements to help mitigate roadway departure crashes
- Lifecycle-based strategies for bridges and pavements could include consideration of whether the assets need widened to support Active Transportation, or long-term mobility.
- Financial plans and investment strategies could include more than only funding to achieve bridge and pavement condition targets. They also could include funds to contribute to broader system performance objectives.

State bridge and pavement programs face additional costs when they consider more than just asset condition targets. However, achieving a SOGR could require considerations beyond the pavement or bridge condition targets. A broader definition of SOGR could strengthen the linkages between asset conditions and system performance.

CHAPTER 2. LINKAGES BETWEEN PAVEMENT CONDITIONS AND SAFETY

This document now turns to more detailed examples of how pavement in good repair contributes to good performance. Research documents the pavement-performance linkage. This is understandable given pavement's link to safety, fuel consumption, and noise, but also pavements' contribution to resilience, environmental justice, mobility, and sustainability.

How Pavements in Good Repair Affect Safety

Research findings on the connection between highway safety and pavement conditions are not always conclusive. The effect of pavement friction and shoulders on crashes is well-documented. However, other pavement-surface effects on safety are less certain. In some research, better surface conditions led to higher speeds and more crashes. In other cases, pavement treatments that increased friction and reduced rutting and hydroplaning lowered crash rates.

To effectively link pavement management and safety, collaboration between TAMP staff, pavement managers, and safety experts may be needed. The TAMP can be one vehicle for such collaboration. The TAMP can help state DOT staff:

- Collaborate across programs to link pavement conditions and safety
- Coordinate funding between safety and pavement programs to maximize each program's results
- Document the State DOT's holistic approach ensuring pavement conditions support safety objectives

Collaboration between the TAMP stakeholders, pavement managers, and safety experts could be valuable. Together they could identify the specific pavement distresses at specific locations that can reduce crashes and improve pavements.

This document now examines specific pavement conditions and how they link to safety. The document starts first by discussing the pavement friction-safety linkage that could be considered in the TAMP.

The Connection Between Pavement Friction and Safety

By at least the 1950s, engineers found correlations between low friction values and highway crashes.[1,2,3] "Double the skid resistance and halve the accidents," is a quote from one British recommendation for treating wet-weather crashes which reflects researchers' finding of correlation between crashes and skid resistance[4].

Although that British study and other research indicates a correlation between crashes and skid values, the crash reduction depends upon treating specific pavements with the proper treatment. The role of friction and crash reduction can vary by site and by weather condition.

A TAMP program manager is likely to focus on IRI values, rutting, cracking, and faulting because those relate to the measures and targets the TAMP must address.[5] However, research indicates that in many cases, it is friction and not those metrics that drive pavement-related crash reduction.[6] Also, research into how those measures influence safety has been more limited than other types of safety research.[7]

One study compared the Pavement Serviceability Index (PSI) to IRI and to rutting depth (RD).[8] It found the PSI to be a better measure of pavement-crash correlation than IRI or RD. The New Zealand Transportation Authority (NZTA) has extensively studied pavement conditions and crash rates. It also found a weak correlation between IRI, rut depth (RD), and crash rates.[9] Another study compared a composite pavement-condition index and pavement marking conditions to individual measures, such as RD.[10] The composite measure more closely correlated to crash rates than did IRI or RD. A Florida study produced nuanced findings correlating pavement conditions to crash rates. It concluded that poor pavement conditions, as defined by the State, were associated with less-severe single-vehicle collisions on low-speed roads.[11] The study found that vehicle speeds decreased when road conditions were poor. However, the effect was reversed on high-speed roads. Multiple-vehicle crash severity increased with pavement condition degradation on all road types. The authors of that study concluded that a pavement-safety measure is urgently needed.[12]

Source: iStock

Figure 2. Photo. Heavy rain seen through a windshield.

These nuanced findings suggest close collaboration during TAMP development between State DOT asset managers, safety staff, and pavement managers. The relationship between pavement condition and crashes could influence how to effectively allocate limited pavement and safety funds. Several studies found that a high benefit-cost ratio for friction treatments depends on applying them at the proper locations. Applying them where not needed increases costs and creates more rolling resistance that lowers tire life and fuel economy.[13] An additional complexity is that a site's skid resistance changes over time. Sites that were treated can within five years lose some of their friction.[14] Even changes in seasons, temperature, and monthly precipitation can influence the skid values of a location.[15] In addition, data from Continuous Pavement Friction Measurement (CPFM), combined with crash data and road characteristics, provide significant insight regarding whether friction improvements may reduce crashes. [16]

FHWA's report Evaluation of Pavement Safety Performance notes that as little as 0.002 inches of water reduces pavement friction by 20 to 30 percent.[17] Wet conditions as seen in Figure 2 increase the importance of pavement friction to achieving safety objectives.

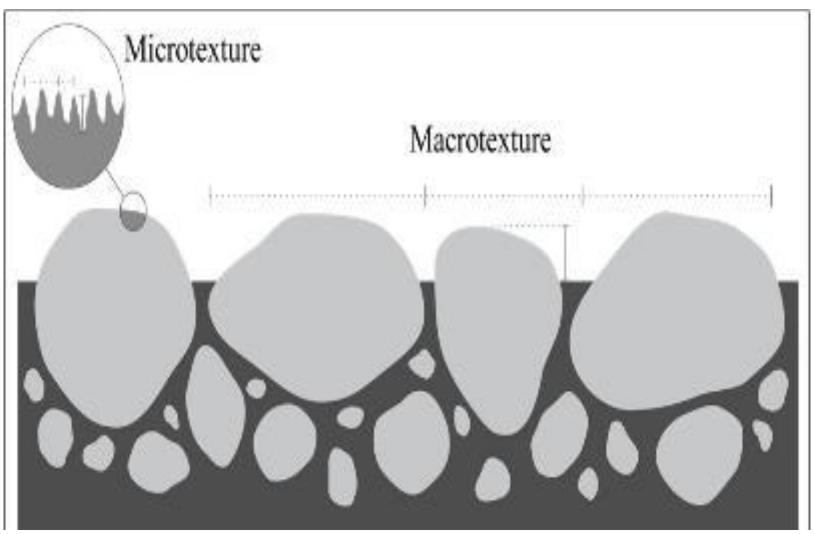
A Texas Department of Transportation (TxDOT) friction research project found clear benefit-cost thresholds.[18] When a location's skid number (SN) was as low as 14, treatment provided a 40-1 benefit-cost ratio. Treating a location with a SN of 28 produced a 20-1 benefit-cost ratio.

When the SN was 73, the treatment's benefit-cost ratio dropped to 1-1. The study documented the significant benefits of maintaining critical SN thresholds. When skid values were above the critical threshold, treatment benefits fell. The critical threshold varies by location.

NZTA supplements its pavement management process with annual system-wide skid measurement.[19] It found that wet weather crashes were occurring primarily on curves that it termed "out of context." Those were ones with high approach speeds or radii that were difficult for a driver to anticipate. A comprehensive approach to addressing SNs produced benefit-cost ratios above 20-1. Those high benefits, however, only occurred on targeted, high-risk sites.

Reducing skid-related crashes depends upon understanding friction's effects[20] (Figure 3). Friction characteristics include a pavement's micro-texture and macro-texture. Micro-texture is the degree of roughness imparted by individual aggregate particles. Macro-texture is the degree of roughness imparted by deviations among particles.[21] Micro-texture and macro-texture are different than roughness. Roughness is measured by IRI. IRI's role in safety will be discussed later.

Decades of research agrees that micro- and macro-texture influence crash rates. However, researchers do not agree upon a minimum skid-resistance threshold, such as the SN, to reduce crashes.[22] FHWA notes that each pavement section's friction demand differs.[23] Friction demand is affected by grade, superelevation, radius of curvature, terrain, and traffic. Travel speed and vehicle mix are also influences. Because these factors can change, no one friction value fits all needs.



Source: Federal Highway Administration.

Figure 3. Diagram. Microtexture and macrotexture.

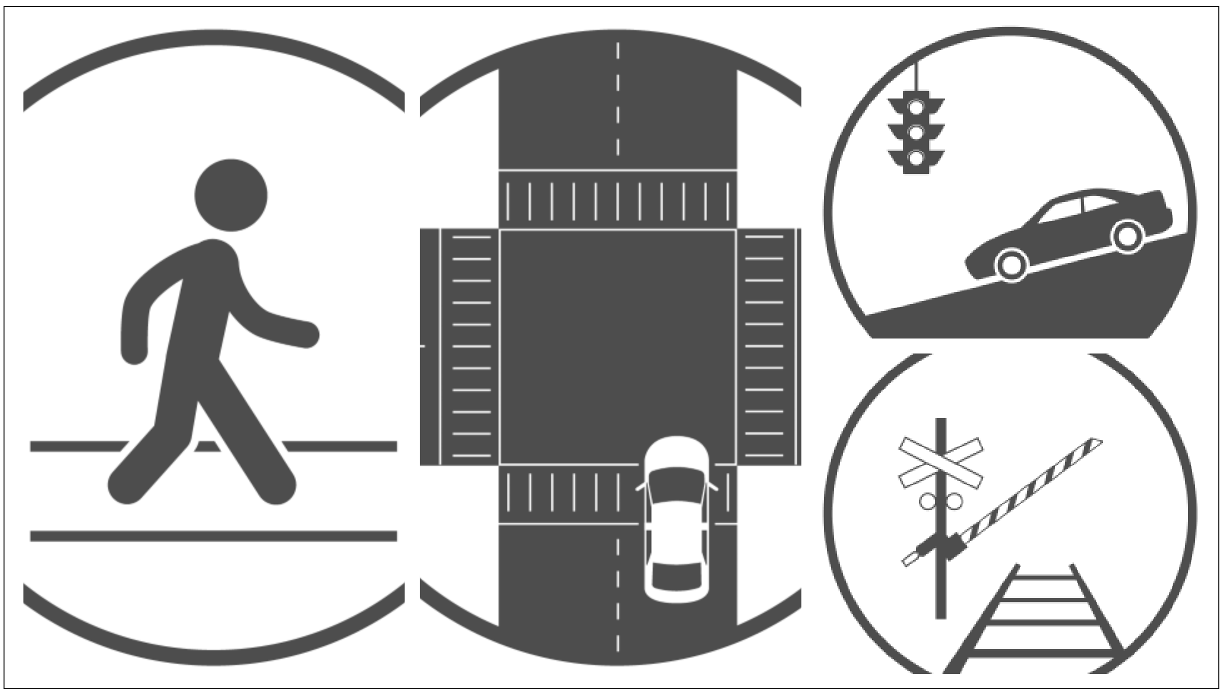
NCHRP Web-Only Document 108: Guide for Pavement Friction[24] recommends that an appropriate level of pavement friction be maintained across all pavement sections. NCHRP Document 108 indicated, however, the appropriate level of friction can vary by site. The document stated that signalized intersections, tight curves, railroad crossings, and pedestrian crossings can be among the locations benefiting from pavement friction treatments.[25]

Intersections accounted for about 28 percent of all fatalities in 2019,[26] making them a prime location for safety improvements. Intersection friction is particularly important to control stopping and turning movements. Those same movements can polish aggregates leading to a loss of pavement friction more quickly than in mid-block roadway sections.

Improved pavement friction at intersections provides numerous benefits including:[27]

- Improved driver control
- Reduced wet and dry stopping distances
- Reduced skidding
- A 20-percent reduction in total intersection crashes[28]

FHWA has noted the critical connection between pavement friction and safety in recommending strategies such as high friction surface treatments.[29] FHWA notes that high friction treatments at curves, ramps, intersections and pedestrian crossings can be applied as a systematic approach to preventive safety using risk factors based on roadway, intersection, or pavement characteristics. One study of high-crash, wet-weather sites reported a 71 percent reduction in wet-weather intersection crashes after friction treatments.[30] Dry-weather crashes were reduced on average 21 percent after friction treatment. Figure 4 illustrates that locations such as crosswalks, intersections, steep grades approaching intersections, or railroad crossings all could benefit from enhanced friction monitoring.



Source: Federal Highway Administration.

Figure 4. Diagram. Locations where friction is particularly important.

Some agencies strategically target skid investigation and treatment on high-risk areas[31] such as crosswalks. Australian state transportation agencies and the NZTA set more stringent friction requirements for pedestrian and school crossings, railway crossings, roundabout approaches, and steep grades.[32]

The City of London mandated high-friction surfacing on pedestrian crossing approaches.[33] It found that the pedestrian crossing accident rate was highest among all low-friction sites assessed using the Sideways-Force Coefficient Routine Investigation Machine technology. Those sites also produced the highest potential casualty-reduction benefits.

One study found different skid values between tunnels and approaches.[34] Precipitation outside the tunnel can lead to water entering the tunnel. The moisture can dry at different rates between the tunnel and approaches leading to differing friction levels.

State DOT TAMPs could address opportunities to both enhance pavement condition and pedestrian safety. The safety and pavement program could share data, pool resources, and look for opportunities to enhance pavement condition and safety performance.

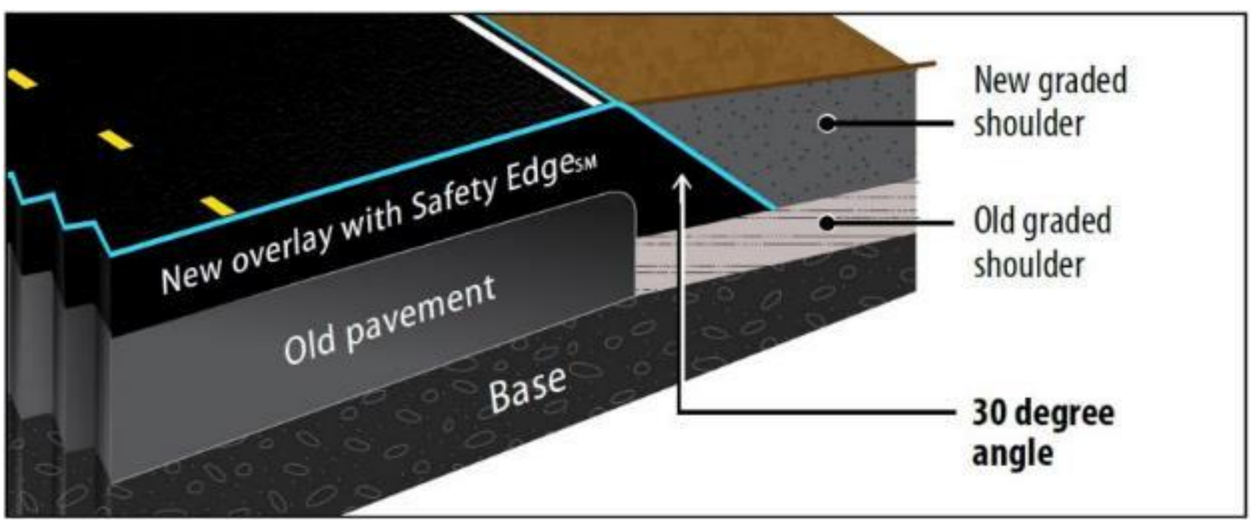
Improving Pavement Friction and Shoulders at Horizontal Curves

The TAMP-development process also could facilitate collaboration between safety and pavement programs to reduce horizontal curve crashes.

FHWA’s guide, Low-Cost Treatments for Horizontal Curve Safety,[35] states that adequate pavement friction and proper shoulder designs can reduce horizontal-curve crashes. On two-lane roads, horizontal curve crashes can exceed by three times those at tangents. Severity of curve-related roadway departure crashes also was higher.

The guide recommends considering pavement-related horizontal curve treatments of high-friction surfaces, pavement grooving, shoulder improvements, and rumble strips. All are low cost and can be added to paving projects, both at individual sites and system-wide. The guide noted one study indicated that the Safety Edge contributed to a 6 percent two-lane road crash reduction.

The Safety Edge is a simple but effective solution that can help save lives by allowing drivers who drift off highways to return to the road safely.[36] As seen in Figure 5, instead of a vertical drop-off, the Safety Edge shapes the edge of the pavement to 30 degrees. Research has shown this is the optimal angle to allow drivers to re-enter the roadway safely. The asphalt Safety Edge provides a strong, durable transition for all vehicles. Even at higher speeds, vehicles can return to the paved road.

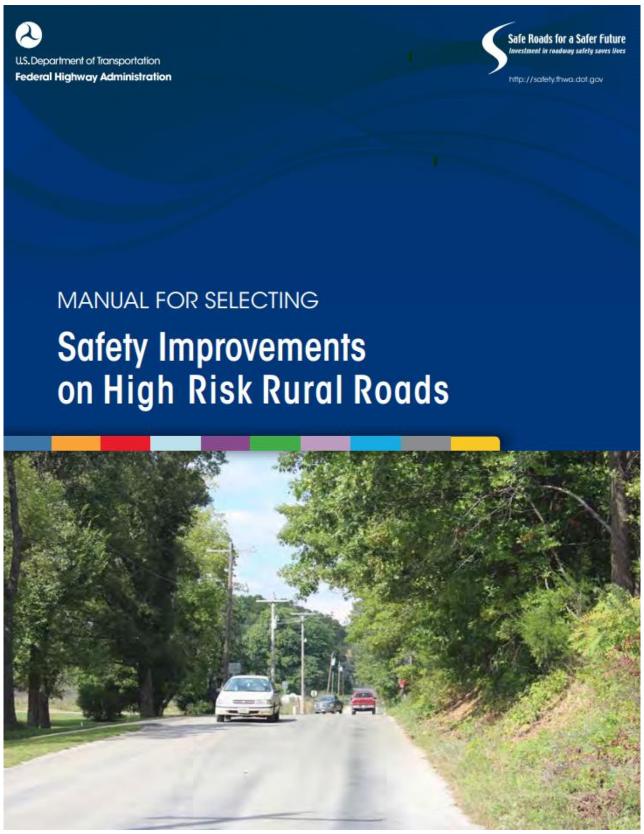


Source: Federal Highway Administration.

Figure 5. Diagram. The safety edge.

Other horizontal curve strategies involve increasing friction and adding rumble strips. Pavement grooving was reported in at least one case to reduce wet-pavement curve crashes by 55 percent, and dry-road crashes by 23 percent. The FHWA horizontal curve safety guide noted that different studies produced different rumble-strip crash-reduction benefits. One of the more recent studies was from Minnesota.[37] It found on rural two-lane, undivided roads centerline and shoulder rumble strips combined reduced crashes 27 percent. The study found crash-reduction values differed slightly by crash type. The study also found, however, that on two-lane roads, rumble strips reduced all crash types.

Pavement Conditions and Safety Improvements on High-Risk Rural Roads



Source: Federal Highway Administration.

Figure 6. Photo. *Manual for Selecting Safety Improvements on High-Risk Rural Roads*.

The collaboration between safety and pavement funding can also be extended to another area of the TAMP. The TAMP could link pavement condition and safety performance to High-Risk Rural Road (HRRR) efforts. An HRRR is defined as, “any roadway functionally classified as a rural major or minor collector or a rural local road with significant safety risks, as defined by a State in accordance with an updated State strategic highway safety plan."[38, 39] FHWA suggests that improving pavement friction, enhancing shoulder treatments, and adding rumble strips can increase a pavement’s contribution to rural safety.[40]

The FHWA *Manual for Selecting Safety Improvements on High-Risk Rural Roads* (Figure 6) recommends each State should implement policies and procedures to incorporate the Safety Edge. It recommends the Safety Edge where pavement and non-pavement surfaces differ by 2.5 inches or more. The Manual also recommends evaluating earthen, graded, or paved shoulders to enhance vehicle recovery and reduce run-off-the-road crashes.

As has been mentioned about intersections, crosswalks, and other high-risk locations, friction monitoring and treatments at high-risk rural sites may promote safety.

The Connection Between Rutting and Highway Safety

Another pavement distress that influences the overall system performance is rutting. Although many researchers have studied the causes of pavement rutting, research on rutting’s safety effect is less common. The primary safety risk associated with excess rutting is hydroplaning or water accumulated in the wheel path.[41]mph).

One study[42] suggested that at speeds less than 37 mph, rut-induced hydroplaning was not a safety concern. However, at speeds greater than 50 mph, RD and length were wet-weather crash factors. This study, and others,[43] noted that rut length is a crash factor and not just RD. This study concluded that the roadway speed should be an important rutting remediation factor.

At least two reports found that a rutting depth greater than .2 inches raised hydroplaning risks.[44, 45] A study of Tennessee freeways found that RD was a good predictor of nighttime wet-weather crashes.[46] It concluded that mitigating RDs could be an effective safety strategy if night-time, wet-weather crashes are elevated.

IRI and Highway Safety

Achieving acceptable IRI targets is frequently discussed as a TAMP's pavement objectives. However, research into the linkage between IRI and safety is contradictory. Some studies found that high IRI values led to increased crash rates and others found they correlated to lower crash rates. Some of the studies found IRI's relationship to crash rates varied by roadway classification and speed limits. Other studies found that composite indicators, such as the PSI that capture multiple distresses, such as seen in Figure 7, are better indicators for crash potential then are individual measures, such as IRI.

Source: iStock.

Figure 7. Photo. Severe pavement distresses.

The variation among research findings further justifies the need for cross-discipline collaboration. TAMP managers, safety staff, and pavement managers may need to analyze their roadways' correlation between IRI and crashes. The research indicates that no simple relationship exists between IRI and crashes that universally can be assumed.

Researchers for one Tennessee study[47] developed 21 regression models of pavement distresses, environmental conditions, and crashes. In studying IRI's link to crashes, they concluded as IRI increased so did its correlation to night-time and wet-weather crashes. Crashes during the peak hour were also slightly elevated over non-peak hours as IRI increased. The researchers found a much higher correlation between PSI and crashes. PSI incorporates several distresses and can include more detail on the type of cracking and distresses, such as aggregate polishing.[48] The Tennessee study found that if PSI deteriorated by one unit, accident frequency increased by 41 percent. PSI is determined on a 0-5 scale, with 5 being the highest. It concluded that PSI should be considered in a comprehensive approach to integrate safety factors into pavement management. The Tennessee study further reinforced the role of pavement condition on the overall system performance.

A study from Jordan examined the relationship between road surface conditions and crash rates.[49] It used regression modeling and a data set of 1,300 road kilometers. It found a significant influence on single-vehicle and multiple-vehicle crashes but noted a contrast in the direction of the influence. Increasing roughness reduced the single-vehicle crash rate while increasing the multiple-vehicle crash rate. The study could not identify a distinct relationship between road roughness and total crash rate.

A Texas study associated lower mean crash severity with poor IRI scores, or values of more than 171 inches per mile.[50] The researchers concluded that poor pavement IRI leads to lower speed and reduces crash severity. Their analysis also showed that crash severity is higher on smoother pavements. However, the researchers reported that crash severity differences could be minor. The crash rate difference between road segments with poor conditions compared to fair/good conditions was only 3 percent.

Another study examined the correlation between IRI, RDs, and crash rates in Arizona, North Carolina, and Maryland.[51] In all cases, the crash rates did not show substantial increases until IRI exceeded 210 inches per mile, or the RD exceeded 0.4 inches. When the IRI or the RD rose above those values, the crash rate increased. The study also found that each State's key threshold values differed. It attributed those State differences to measuring equipment, data processing methods, or sampling methods.

Although the effect of IRI by itself on crash rates may vary, research indicates that pavement condition overall is important. One study found that on two-lane roads, pavement condition was the third most significant crash predictor after average daily traffic and lane width.[52]

Research by the Institute for Transportation of Iowa State University developed a weighted condition index that combines multiple condition indicators into an Asset Condition Index (ACI).[53] This method allows linking condition indicators to safety while minimizing the variation caused by different individual indices. In this study, multiple individual asset condition measures were scored, given weights, and summed up into a single ACI for each road segment. The sub-index measures were:

1. IRI
2. Faulting
3. Friction
4. Rutting
5. White pavement marking retro-reflectivity
6. Yellow marking retro-reflectivity

This approach avoids the complications of multiple condition measures and their different, sometimes contrasting, safety effects. To obtain each section's ACI, the individual condition measures were scored. ACI values range from 1, which is poor, to 3, which is good. A higher

ACI reflected better conditions. Measures' safety effects were weighted. Statistical analysis concluded that crash numbers decreased as the ACI increased, or as the six sub-indices improved. It also found correlation between low ACI values and crash frequency.

Using benefit-cost analysis, the study recommended minor rehabilitation and durable pavement marking materials as the most cost-effective treatments. Those are most cost effective in the short term for all ACI values and over the long term for ACI values above 2.0 When ACI values were low, then major rehabilitation and use of tape marking were recommended as cost-effective treatments.

As seen in Figure 8, a number of factors, including high pavement friction and adequate shoulders, combine to improve roadway safety, particularly under wet conditions.

Source: iStock.

Figure 8. Photo. A wet, winding rural road.

Pavement Conditions and Crash Modification Factors

While the initial TAMPs have typically focused on IRI, rutting, cracking, and faulting, research has not advanced to the point that robust crash modification factors (CMFs) exist for those distresses. To date, pavement CMFs primarily focus on friction. Fewer studies produced CMFs for IRI, rutting, cracking, or faulting. The lack of simple correlation between those pavement distresses and safety could require close collaboration between State DOTs' safety and pavement staffs. Each State may need to see if correlations exist on their roads for those distresses and elevated crash rates. A CMF is a multiplicative factor that indicates the proportion of crashes that would be expected after implementing a counter measure.[54] The lower the CMF, the more crash reduction. For example, a CMF of 0.5 would reflect an estimated 50 percent crash reduction when applied to the base crash numbers. A CMF above 1 predicts crash increases after treatment.

The Crash Modification Clearinghouse does not indicate that many highly ranked CMFs exist for measures, such as improving IRI, rutting, or cracking. The quality of a CMF is ranked on a 1-to-5-star rating. Highly ranked CMFs exist for friction, but fewer exist for other pavement-surface-related measures.

CMFs do exist for friction treatments, pavement safety edge, shoulders, and many preventive maintenance treatments.

For example, the CMF identification number (ID) 194 is for treating intersection approaches with high friction surfaces. It has an overall CMF of 0.76, which equates to an expected 24-percent crash decrease if the measure was applied. The 24-percent decrease is for all conditions. The wet-road CMF is higher at 0.43, or a 57-percent crash reduction. The CMF for high-friction treatments for rear-end crashes predicts a 42-percent crash reduction.

The above CMFs for high friction surfaces have a 5-star rating.[55] At least one set of CMFs were included in the Clearinghouse for IRI and crash severity. They received a no-star rating because of insufficient available data.

Although CMFs for treatments other than friction treatments are few, CMFs exist for roadway shoulders and pavement edges.

CMF ID 6202 is for the safety effects of shoulder paving for rural and urban Interstates, multilane, and two-lane highways. It shows a CMF of 0.57 for widening an Interstate highway shoulder from 0 to 6 feet and of 0.38 for adding an 8-foot Interstate shoulder. At the lower range of effectiveness were re-paving deteriorated 2-foot shoulders. For non-Interstates, the CMF for reducing fatal crashes was 0.81 when a 2-foot shoulder was added. For other types of crashes, CMFs for paving a deteriorated 2-foot shoulder ranged from 0.99 to 0.85.

Pavement Preservation and Its Nexus with Highway Safety

Another nexus of asset management and safety the TAMP could consider occurs with pavement preservation. Low-cost pavement treatments often drive a lifecycle-based pavement preservation investment strategy. The same treatments that can extend pavement life also can influence pavement friction. Understanding how low-cost preservation treatments influence safety can improve both pavement and safety performance and contribute to the overall system performance.

The FHWA report on Evaluation of Pavement Safety Performance examined how low-cost pavement treatments affect safety.[56] The study examined multiple pavement treatments:

- Chip seals, both single and double layer (Figure 9)
- Diamond grinding concrete pavements
- Grooved concrete pavements
- Microsurfacing of both asphalt and concrete pavements
- Open-graded friction course (OGFC), both asphalt and concrete
- Asphalt slurry seals, cape seals, scrub seals, and micro-milling
- Thin hot-mixed asphalt (HMA) on both asphalt and concrete
- Ultra-thin bonded wearing courses (UTBWC) on both asphalt and concrete

- Shotblasting and Abrading on both asphalt and concrete
- High Friction Surfacing (HFS) on both asphalt and concrete

The study reinforced other research that indicates that the safety effects of pavement-surface treatments can vary. In some cases, in some States, the data indicated improved safety performance. In other cases, crashes increased after some treatment types, or on some types of roads. The research further reinforced that pavement effects vary by traffic volumes, functional classes, weather, and other factors.

Source: Washington State Department of Transportation.

Figure 9. Photo. A chip sealed road.

The study compiled data from 17 States. Researchers studied the before-and-after crash histories of sites receiving one of the low-cost treatments. However, no friction testing was conducted as part of this study. For wet-weather crashes, the research concluded that the combined study results for all treatment types suggest benefits for reducing crashes. Exceptions were for thin HMA treatments in California and North Carolina. Those two States' datasets were large enough for definitive results. The OGFC for two-lane and multi-lane roads produced negligible wet-weather benefits.

For dry-roads, crashes increased for microsurfacing on two lane roads, except in North Carolina. Also increasing were crashes on roads treated with thin HMA and OGFC on two-lane roads, and chip seals on multilane roads. The study produced indications of benefits for the ultra-thin bonded wearing course, chip seals, and slurry seals on two-lane roads. Also, diamond grinding on freeways produced crash-reduction benefits.

Despite a rigorous regression analysis, the study concluded that the research's CMFs were not robust enough for recommended use. The results suggested, however, that there are relationships between the CMFs and Annual Average Daily Traffic, and sometimes precipitation, urban-versus-rural settings, and expected crash frequency.

The study results examined only safety benefits, and not pavement lifecycle benefits. Also, intersections were not studied, so any effects there would not be included.

The study concluded that benefit-cost ratios larger than 2.0 were found for selected applications in certain States including:

- Chip seals on two-lane roads
- Freeway diamond grinding
- Thin HMA on North Carolina multilane roads
- OGFCs on freeways
- Slurry seals on two-lane roads
- UTBWCs on two-lane roads

Another recommendation the study reinforced was the need for each State's pavement and safety experts to consider their State's unique results. The broad national study concluded that more specific information was needed to reach further conclusions. Data needed were more specific information about sites' friction, texture, and pavement condition. The study suggests, but did not definitively conclude, that some of the non-intuitive crash increases may be caused by:

- Smoother, quieter pavement leads to higher speeds, particularly for local drivers who are accustomed to the roadway and perceive it to be safer after treatment.
- Elimination of cracking, rutting, and other distresses could lead to higher speeds.
- Porous surfaces reduce splash and spray and may improve wet-weather visibility that may reduce crashes.

Although the study does not recommend using its CMFs, its estimated CMFs illustrate the variability the study found. In California, the study produced an estimated CMF for chip sealed roads overall of 0.908. That would indicate a more than 8 percent crash reduction. In Minnesota, the overall estimated CMF for chip seals on all roads and all conditions was 1.25. That indicates a 25-percent crash increase.

For wet weather crashes, the California results for multi-lane chip seals in wet weather produced a very strong CMF of 0.423. Conversely, the overall wet-road chip seal CMF in Minnesota was 1.604.

In general, however, the CMF for all two-lane chip sealed roads studied was 0.939, indicating more than a 6-percent crash reduction. For wet-road crashes, the chip seal CMFs indicated crash reductions in all cases, except in Minnesota. The study concluded that the chip seal benefits overall were positive for crashes on two-lane roads.

The other results found included:

- For diamond grinding concrete pavements, the study found benefits for both wet and dry-road crashes. The CMF for all wet-road freeways was 0.869 and for all freeways it was 0.943.

- Thin HMA treatments produced wet-road benefits on multilane routes and freeways. No effect was found for overall dry-road crashes.
- OGFC produced mixed benefits. Benefits were negligible for wet-road two-lane and multilane crashes, but substantial on freeways. North Carolina showed benefits in all categories from OGFC, particularly on wet road run off the road (ROR) crashes. However, the California CMF for dry road two-lane crashes was 1.12.
- Grooving results were limited to California. It showed a CMF of 0.776 for all crashes. Wet road crashes increased, but data were too limited for statistically valid results.
- For microsurfacing, wet-road crashes decreased and dry-road crashes increased overall, resulting in a net crash increase. For all two-lane roads, the overall CMF for microsurfacing was 1.09. For all two-lane wet-roads it was 0.867.
- For slurry seals, data were largely available for California. There were wet-road benefits and weak apparent dry-road benefits. The overall California slurry seal CMF was 0.936, and 0.621 for wet-road ROR crashes.
- UTBWCs produced substantial benefits for wet-road, two-lane crashes with a wet-road CMF of 0.694. The two-lane, wet-road ROR CMF was 0.550.

The study's overall results showed safety benefits to most low-cost pavement treatments. The study benefits were limited to crash reduction. The study stated if the pavement lifecycle savings were included, the overall benefits could have been higher.

The study results reinforce that pavement preservation and safety concerns should be jointly evaluated. The study results also indicate that in many cases, but not all cases, both safety and pavement performance can be accomplished by appropriate pavement treatment selections. The TAMP analysis could be a vehicle for conducting the pavement-safety analysis and documenting the state DOT's strategy to improve overall system performance.

How Pavement Programs Can Support Pedestrian Safety and Mobility

Another TAMP opportunity to achieve overall improved system performance is to link pavement programs with safety programs' efforts to reduce pedestrian and bicycle crashes. Between 2010 and 2019, pedestrian fatalities grew from 4,301 to 6,205, a 44-percent increase.[57] Traffic crashes injured another 76,000 pedestrians and 49,000 pedalcyclist in 2019. Combined pedestrian and pedalcyclist fatalities represent 19.5 percent of 2019 traffic fatalities.[58] That is up from 14.9 percent in 2010.

About 10.4 percent of the NHS centerline miles are under local control, with 62 percent of those miles owned by municipalities.[59] Those NHS miles are likely to pass through urban and suburban neighborhoods with pedestrians, bicyclists, and other vulnerable road users. Also, many non-NHS State routes included in TAMPs pass through urban areas with high pedestrian and cyclist numbers. When State DOTs coordinate their TAMPs with regional transportation plans, they may find a nexus between their pavement programs, pedestrian safety, and environmental justice. For example, the Atlanta Regional Commission's (ARC's) Safe Streets for Walking & Bicycling plan notes the region's increase in pedestrian and bicycle crashes, and how they are disproportionately in communities of color.[60] It reported that in Georgia, Black pedestrians were 1.68 times more likely to be killed than white pedestrians. ARC adopted policies prioritizing pedestrian safety programs in high-crash areas, such as Black and Hispanic neighborhoods.

In the Twin Cities of Minnesota, the Metropolitan Council's Regional Pedestrian Safety Action Plan also found that Black and Native communities are disproportionately harmed by pedestrian crashes.[61] It found that 14 percent of pedestrian deaths were among Blacks, whereas they were 9.6 percent of the region's population. The study led to a prioritization measure for funding pedestrian safety projects.

The Indianapolis Metropolitan Planning Organization Regional Pedestrian Plan also notes the disproportionate need for improved sidewalks and pedestrian facilities in low-income and minority neighborhoods.[62] It notes that investments are part of a larger strategy to both reduce pedestrian crashes and increase equity in transportation investments.

National research concludes that people of color are more vulnerable to pedestrian crashes.[63,64,65] Reasons include much affordable housing is near high-speed roads. Also, communities with affordable housing may not have the resources to pay for roadway improvements that include pedestrian safety enhancements or even sidewalks. People with low incomes are also less likely to own cars and are twice as likely to walk compared to people with higher incomes.[66,67]

Low-income urban areas that experience elevated pedestrian crashes often have similar roadway characteristics.[68] Many low-income neighborhoods are divided by high-speed/high-volume arterials. Other characteristics include a density of traffic signals and bus stops, as well as higher posted speed limits. An injury-severity model indicated a correlation with a lack of street lighting, as well.

Several studies concluded[69,70] that areas with a greater density of pedestrian-oriented roadways were associated with fewer pedestrian crashes. Those findings indicate that wealthier areas experience fewer pedestrian crashes.

States' pavement program managers can collaborate with safety staff, local stakeholders, and active transportation advocates to link pavement-treatment strategies to pedestrian safety and mobility. Such collaboration could occur at the program level with safety staff and pavement staff developing policies to ensure that urban pavement reconstruction projects are developed with pedestrian safety as an objective. That policy could result in project-level coordination between a community, the project designer, and the State DOT's safety and pavement staff to incorporate pedestrian safety features in pavement reconstruction projects.

One pavement-safety linkage discussed earlier in this document involves pavement friction. Ensuring adequate pavement friction at intersection and mid-block crosswalks (Figure 10) could be one technique to link pavement-treatment strategies with safety.

Source: iStock.

Figure 10. Photo. Children crossing a street via a crosswalk.

Other efforts could be TAMP policies to consider the safety needs of streets when pavement rehabilitation projects are planned. A State DOT's limited pavement budget probably is not adequate to afford the safety enhancements urban NHS or State highways may need. However, the process of developing TAMP investment strategies could provide a venue for coordinating efforts. The pavement program, the safety program, active transportation programs, and even metropolitan planning organizations (MPOs) could coordinate. Pooling funds from several programs could provide more pedestrian safety benefits than funding from only the pavement program.

The need to coordinate pavement strategies with urban safety efforts could influence the TAMP investment strategies. Pavement investment strategy allocations could include amounts for additional safety-related costs. Without reliable pavement funding sources, pavement program managers may lack funds to address safety enhancements.

Some treatments that could be associated with pavement rehabilitation projects could include several proven countermeasures FHWA recommends such as:

- **Median and pedestrian refuge islands**—A Maryland study identified a 14-percent reduction in pedestrian or bicycle crashes when median treatments with pedestrian islands were installed.[71] A crash reduction factor (CRF) of 56 percent was reported in one source for installing pedestrian refuge islands.[72]
- **Sidewalks**—Installing a sidewalk to avoid walking on roadways is associated with high CFRs of up to 74 percent.[73]

- **Crosswalk Visibility Enhancements**—Three main crosswalk visibility enhancements help make crosswalks and their users more visible. These include high-visibility crosswalks, lighting, and enhanced signing combined with pavement markings.[74]
    - FHWA reports high-visibility crosswalk improvements can reduce pedestrian injury crashes by 40 percent.
    - Intersection lighting can reduce pedestrian crashes by up to 42 percent.
    - Advance yield or stop signs combined with pavement markings can reduce pedestrian crashes by 25 percent.

CHAPTER 3. PAVEMENT CONDITIONS OPERATING COSTS AND NOISE

Although TAMPs do not address user costs, pavement conditions (Figure 11) affect user costs. Reducing user costs could be an agency objective that indirectly affects the TAMP.

Researchers[1] include the following as condition-related vehicle operating costs:

- Fuel
- Repair and maintenance
- Tire wear
- Capital cost and depreciation
- Oil consumption
- Licensing and insurance

Some costs are not condition-related and occur whether the vehicle travels or not. These include depreciation, insurance, licensing, and parking. Other costs directly relate to roadway conditions. These include fuel consumption, repair and maintenance, and tire wear. A societal or environmental cost also could be the greater emissions that occur when rough pavement increases fuel use. This report will consider emissions and environmental costs later.

The World Bank developed the most commonly used Highway Development and Management System vehicle operating cost model with updates between 1971 and 2019.[2] A version of the model was updated by National Cooperative Highway Research Program (NCHRP) researchers in 2012. The 2012 NCHRP research determined that the widely used World Bank model underestimated how pavement roughness increased fuel consumption. The 2012 research indicated that pavement roughness often had twice the effect on fuel consumption as previously thought.

Source: iStock.

Figure 11. Photos. A severely cracked compared to a smooth pavement.

Tripling IRI from a smooth 63 inches per mile to 190 inches per mile increased passenger car fuel consumption by 4.8 percent compared to the World Bank's model predicted 2.8 percent. The NCHRP research showed that for sport utility vehicles (SUVs), fuel consumption increased

4.1 percent; for vans it increased 1.8 percent, for light trucks it increased 1.6 percent, and for tractor-trailers it increased 2.9 percent. All the predicted fuel-consumption increases were more than double that predicted by the World Bank model. In some cases, the new findings tripled the predicted pavement roughness effect on fuel consumption.

To put the research findings into context, 23 CFR 490.313 considers IRI less than 95 to be good; between 95 and 170 is fair, and more than 170 is poor.[3]

Effects on tire wear and repair and maintenance were also found. No increase in passenger car repair and maintenance costs were found for IRI increases below 190 inches per mile. IRI values between 190 and 253 increased repair and maintenance costs by 10 percent. IRI values above 317 increased repair and maintenance costs of passenger cars by 40 percent, and 50 percent for heavy trucks.

For tire wear, each increase in IRI of 63 increased wear by 1 percent for both passenger cars and trucks.

The nationwide estimated savings from smoother pavements were significant. A decrease in IRI of 63 inches would result in a 3 percent passenger car fuel consumption reduction. The 2012 study equated such a reduction to a national savings of 6 billion gallons annually. Tire wear savings were estimated as $340 million annually. Vehicle operating costs varied by vehicle class and other factors. However, improving IRI by 63 inches produced an estimated annual vehicle repair savings of between $24.5 billion and $73.5 billion in 2012 dollars.

Pavement Condition and Noise

As State DOTs consider how to both manage pavements and enhance the quality of life, reducing roadway noise could support the agency's mission. Reducing noise also could address a provision in the asset management rule in 23 CFR 515.9(d)(1). The asset regulation notes that TAMPs must include objectives that should align with the State DOT's mission.[4] An element of both achieving the agency's mission and managing pavements could include consideration of the noise impacts influenced by pavement conditions.

If an agency's TAMP includes "quality of life" objectives that support the agency's mission, then pavement noise also could be a consideration. Pavement surfaces can be a significant influence on the noise that affects human health, property values, and the overall quality of life. The World Health Organization (WHO)[5] attributes excessive noise to cardiovascular disease, children's cognitive impairment, sleep disturbance, tinnitus, and annoyance. A WHO noise policy indicated highway traffic noise was the largest source of sleep disturbance and annoyance. Sleep disturbance and annoyance were noise's largest health impacts. One study indicated traffic noise was equal to second-hand tobacco smoke as an environmental health risk.[6]

Researchers also found that excess highway noise lowers property values. Researchers in the Memphis, TN, area studied residential properties exposed to noise levels above 45 decibels. They concluded such properties suffered from an "environmental noise discount on housing values."[7] The price discount increased linearly as noise levels rose. That study confirmed at least two European studies that found excess highway noise decreased home values by up to 30 percent.[8,9]

FHWA's Little Book of Quieter Pavements[10] noted that noise barriers can be expensive and are not always effective. They are of questionable effectiveness in rolling terrain or where arterial streets create barrier gaps. FHWA's publication noted that more densely populated European and Asian countries pioneered quieter pavements to lower highway noise. Increasingly urbanized U.S. residents are now also demanding quieter highways.

FHWA notes three factors that contribute to highway noise: propulsion, tire-pavement interaction, and aerodynamics. At low speeds, vehicle propulsion noise dominates. At higher speeds, tire-pavement noise dominates with heavy trucks being 10 times louder than passenger cars. It is louder, higher speed noise that quiet pavements can improve.

FHWA's The Little Book of Quieter Pavements recommends the following strategies:

- Small surface texture of less than 5 millimeters (mm)
- Porosity that can absorb road noise and reduce contact area, balanced with pavement-durability needs
- Stiffness reduced but without compromising pavement quality. This is the most difficult of the three strategies to achieve

FHWA Technical Advisory 5040.36 addresses the texture requirement for noise reduction. Minimizing the tire noise can be achieved through a friction management plan that aims to maintain the macro-texture and micro-texture at an optimized level. The linkage between friction and noise illustrates another of the cross-cutting linkages between asset condition and asset performance.

CHAPTER 4. HOW BRIDGES IN GOOD REPAIR CONTRIBUTE TO PERFORMANCE

Less research exists for bridges' linkage to performance than for pavements. Nonetheless, good-condition bridges are essential to a high-performing transportation system. This section examines the linkage between bridge conditions and performance including:

- Structures can contribute to freight mobility when they can accommodate super loads or are not load limited.
- Bridges can support mobility when they have the width to accommodate needs for transit services, Active Transportation, or sufficient travel lanes.
- Bridges can enhance communities when they incorporate aesthetic or historic elements reflecting their surroundings if the TAMP includes "quality of life" objectives.

Bridges and Active Transportation

Source: iStock.

Figure 12. Photo. A multiuse path on a bridge.

The condition of a bridge is based upon the criteria set in 23 CFR 490.409. Those criteria determine if a bridge is rated in good, fair, or poor condition. Minimum levels for the condition of bridges are set in 23 CFR 490.411. Penalties for not maintaining bridge conditions are set in 23 CFR 490.413.

In addition to those criteria about bridges' condition, TAMPs could include additional factors for their bridge performance objectives. Objectives, in addition to achieving a condition level, could include factors such as:

- Supporting active transportation, where appropriate, by providing pedestrian or bike lanes, such as in Figure 12
- Providing lanes or grade separations for bus rapid transit or other transit alternatives
- Alleviating passenger or freight bottlenecks
- Integrating into community plans for Complete Streets or livable communities if the TAMP includes objectives to support those efforts

States have the latitude to adopt policies that consider how a bridge meets multiple performance objectives, in addition to its condition targets. A bridge could meet condition targets but not achieve the State's performance objectives.

For example, urban bridges may not accommodate Active Transportation and impede the State's mobility objectives. A long-term objective for urban structures could be to consider adding bike and pedestrian lanes when bridges are scheduled for rehabilitation or replacement.

Planning to add Active Transportation lanes to bridges could take many years and exceed the TAMP horizon. The long bridge planning horizon provides an opportunity to link the TAMP with the LRSTP. The LRSTP and the TAMP could both incorporate policies that bridge planning will incorporate active transportation considerations. Not every bridge may need to accommodate Active Transportation, but for those that do, adequate width could allow the structure to support additional system performance objectives.

Bridges and Mobility

If the bridge appears on the State's list of high-congestion locations, its width may be a mobility performance impediment relevant to both the TAMP and the congestion programs. Each year, FHWA publishes a list of the top 100 Interstate System congestion bottlenecks.[1] Most of them are at major interchanges that include bridges. An opportunity for considering both bridge condition and bridge performance occurs if the State DOT coordinates its congestion strategies with its bridge lifecycle strategies. How well a bridge performs could factor into the long-term, lifecycle strategy to rehabilitate or replace a structure. As seen in Figure 13, the Minnesota Department of Transportation (MnDOT) modified freeway bridges to complement a new bus rapid transit and light rail in the Twin Cities.

Source: MnDOT.

Figure 13. Photo. A bridge modified to accommodate transit.

Although the term of "functionally obsolete" is no longer tracked by FHWA for performance measurement,[2] the concept may have relevance to State DOTs as they link planning for asset management, mobility, and freight movement. Functionally obsolete is defined in 23 CFR 661.5 as "the state in which the deck geometry, load carrying capacity (comparison of the original design load to the State legal load), clearance, or approach roadway alignment no longer meeting the usual criteria for the system of which it is an integral part."[3] Urban bridges that do not accommodate Active Transportation or that cause congestion could be considered functionally obsolete if a State or MPO chose to identify them as such.

Bridges and Freight

Similar to mobility considerations are bridge performance and freight considerations important to both the TAMP and the Freight Plan. Two trends overlap with bridge lifecycle planning (LCP) and freight planning. First, bridges on the National Highway Freight Network (NHFN) are aging. In a report to Congress,[4] FHWA noted that nearly 31.5 percent of bridges on the NHFN are 51 years old or older. More than 53 percent are between 26 and 50 years old (see Figure 14).

Second, freight volumes continue to grow. FHWA's Freight Analysis Framework (FAF4) predicts that domestic U.S. truck tonnage will increase from 12.4 billion tons in 2020 to 16.4 billion tons by 2045.[5] This tonnage moves primarily on the NHS and its bridges. FHWA statistics indicate the NHS is only 8.7 percent of all public lane miles but carries 55 percent of all vehicle miles travelled.[6] The truck freight comprises 10.4 percent of all vehicle miles traveled in 2020.[7]

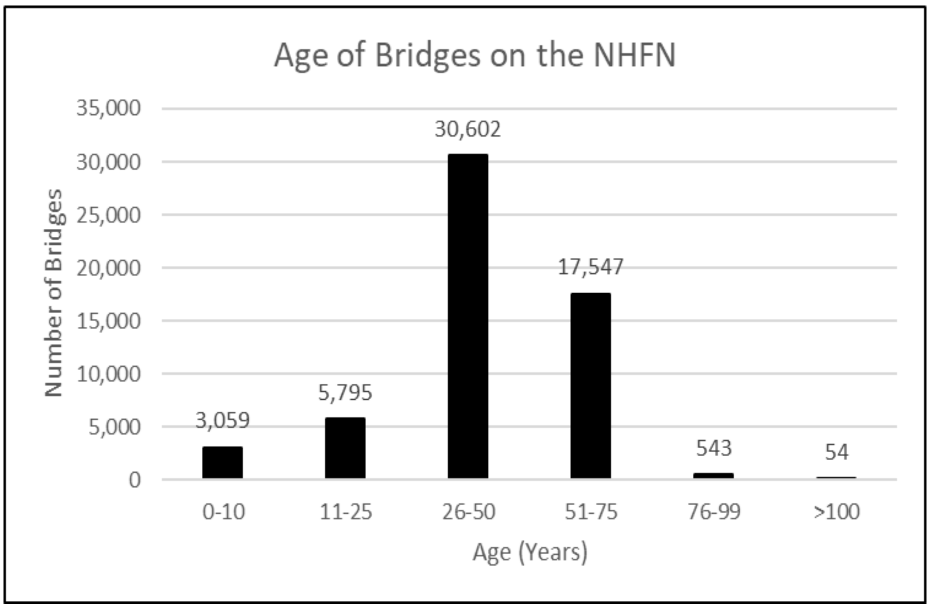


Figure 14. Graph. Age of bridges on the National Highway Freight Network.

The National Freight Strategic Plan (NFSP) emphasized that addressing the Nation's highway freight needs will involve complex transportation planning issues, particularly in urbanized areas.[8] Among those issues is how to maintain bridge conditions while supporting mobility, safety, and community livability.

As State DOTs develop lifecycle plans for these important NHS structures, they have the opportunity to link the State Freight Plan and TAMP. As bridges enter the 26 to 50 age range, State DOTs often plan to rehabilitate them to extend their service life. That project-level planning could be done in conjunction with long-term system planning for how to manage the freight system.

FHWA Guidance on State Freight Plans and State Freight Advisory Committees notes that freight plans are only required to have an 8-year horizon, (49 U.S.C. 70202 (d)). However, FHWA suggests State DOTs should consider extending that horizon to provide additional opportunities for linking asset management and freight-congestion strategies.[9] FHWA has stated that a 8-year horizon may not enable States to do more than list current problems and projects already in the pipeline. A horizon of 20 years allows increased linkage with asset management lifecycle strategies for pavements and bridges, as well as with the LRSTP and the MTPs.

Bridges Enhancing Their Surroundings

A frequent way in which State DOTs are using structures to enhance communities is through aesthetic designs. As new bridges, retaining walls, and noise barriers are constructed, State DOTs are frequently incorporating aesthetic treatments. The result can be long-lasting structures that harmonize with their surroundings.

Aesthetics are not a requirement in the asset management, planning,[10] or performance management rules.[11] However, TAMPs could note that bridge program funding amounts help pay for aesthetic treatments where structures are designed to support “quality of life” objectives. Aesthetics, or the loss of them, are considered an Environmental Justice factor.[12] Linking aesthetics to bridge programs could be another way to tie TAMPs to additional performance objectives.

Source: Ohio Department of Transportation.

Figure 15. Photo. A bridge embossed with aviation images.

FHWA’s Guidelines for the Visual Impact Assessment of Highway Projects[13] notes that the public is concerned about projects’ visual appearance. FHWA’s guidelines state that highways are more than functional. They also are extensions of a community’s values and aesthetic preferences.[14] FHWA guidelines state that strategies to address visual impacts should be technically possible and practical. They also need to be politically and financially feasible to the community and organization that will pay for their construction and maintenance.

Bridges and other structures are not the only elements that can be enhanced. FHWA’s visual impact guidelines note that use of native plants, burying utilities, minimizing tree removal, and contouring to mimic the natural landform can be other types of visual impact mitigation.

However, structures such as bridges and noise walls are among the prominent highway features. Integrating them into their surroundings is one way in which assets in good condition can enhance the attractiveness and livability of their communities. The Ohio Department of Transportation included flight motifs into a series of projects on Interstate 75 and Interstate 70 in and near Dayton, OH (Figure 15). Those commemorate the region’s association with the Wright

Brothers, astronaut Neil Armstrong from nearby Wapakoneta, and with Wright Patterson Air Force Base.

The MnDOT Aesthetic Guidelines for Bridge Design[15] states that bridges are legacies of an individual, a program, or an era. The legacy a bridge leaves reflects the values that initiated the design. The Utah Department of Transportation (UDOT) echoes a similar sentiment.[16] It notes that highways are among a community's most visible components. Once built, they remain visible for generations. Because of their significance and permanence, they should integrate sound design principles and complement their surroundings.

Maryland Department of Transportation State Highway Administration (MOT SHA) guidelines emphasize that aesthetics are often linked to design efficiency.[17] Some of the most iconic bridges are also some of the most economical. Both the Maryland and the North Carolina Department of Transportation[18] emphasize that shape and proportions are among the most important elements. The same considerations that can make a bridge attractive can also make it economical.

CHAPTER 5. PAVEMENTS AND BRIDGES IN A CHANGING CLIMATE

This section will discuss the links between asset conditions, asset resilience and performance. In some cases, asset conditions, per se, may not affect resilience. For example, a pavement's IRI or a bridge's deck condition may have little influence on a roadway's flood resilience. In other cases, condition and resilience may be closely linked. Asset management's LCP process provides regular milestones for assessing assets' condition and considering their resilience.

Connections between the SOGR and resilience occur in at least two ways. First, some assets in good condition may be more resilient. An example could be a culvert. If its components are clean and functioning as designed, it is more likely to perform as intended.

Second, asset rehabilitation and replacement cycles provide State DOTs opportunities to incorporate resilient design elements. LCP involves the timely application of preservation, maintenance, rehabilitation, and reconstruction to extend asset life. Each phase allows State DOTs to consider if treatment could enhance the asset's resilience.

In an increasingly unpredictable climate, assets face many threats to their resilience. Storm surges and flooding can wash out roads and slopes, while hurricanes can damage signs, signals, and other traffic control devices. Bridges and culverts can be vulnerable to flooding, scour, wave action, or storm surges. Other threats include seismic events or debris flow from steep, fire-denuded slopes.

Each State faces unique resilience threats and opportunities. Some of the more recent studies of asset condition and resilience concluded that there are few uniformly appropriate system-resilience metrics.[1,2] Too much diversity exists between States' climate, geology, geography, and asset conditions to identify uniform, national resilience measures. Dozens of FHWA-sponsored pilot projects reveal States' diverse resilience needs. FHWA sponsored 11 pilots about Resilience and Durability to Extreme Weather. Another six pilots addressed Asset Management, Extreme Weather, and Proxy Indicators. Five pilots examined Nature-Based Resilience for Coastal Highways, and 19 pilot teams partnered on Vulnerability Assessments and Adaptation Options. Five pilots participated in the earliest efforts which were Vulnerability Assessments. Details on these pilots can be found at the FHWA Resilience Pilots website.[3]

Without "off the shelf" resilience metrics available, each State may need to assess which assets are most vulnerable to which threats. The TAMP-development process could be the forum for diverse stakeholders to identify resilience threats. The TAMP's risk management section could document the State's unique resilience threats. Then, the TAMP lifecycle plans and investment strategies could describe how the State DOT plans to both sustain a SOGR and mitigate resilience threats.

Structures and Resilience

The history of bridge inspection, repair, and retrofitting reflects the long-standing link between bridge condition and performance. The National Bridge Inventory (NBI) established in the 1960s includes several resilience-related items. In 1991, FHWA issued a technical advisory on evaluating scour at bridges.[4] In 1992, FHWA initiated a comprehensive bridge seismic research effort.[5] As discussed earlier in this report, in the 2000s, FHWA began a series of resilience pilot projects to help states identify resilience strategies for bridges and other assets.[6] FHWA in 2016 produced a report titled *Highways in the River Environment – Floodplains, Extreme Events, Risk and Resilience*.[7] These are just a few milestones that reflect a long-standing focus on structures' resilience. Although resilience concerns are not new, they are now more intense. Increased storm intensity and weather variability create new threats that can affect assets' long-term condition and performance (Figure 16). The following brief summaries illustrate, in chronological order, some of the sources mentioned in this paragraph and how the sources link the condition of highway assets to their resilience.

National Bridge Inventory Data

Among the oldest sources of resilience data are the 116 items recorded for the NBI,[8] several of which directly relate to a structure's resilience. These include vertical and horizontal clearances that are relevant to potential truck or barge strikes. Other items include scour criticality, channel adequacy and protection, fracture criticality, and waterway adequacy. Even the rating of structures' components can be considered as a form of measuring resilience. A bridge with a good superstructure and substructure may be more resilient than one with poor components. Other NBI items relate to how critical a structure is to the transportation system. These items include traffic and truck volumes, functional classification, and detour length.

Source: iStock.

Figure 16. Photo. Flood damage to a road.

These NBI items could provide State DOTs with data to develop bridge-resilience measures that relate bridge conditions to their ability to withstand storm events. However, as mentioned below, no group of these NBI items alone appear to be predictors of bridge failure during major hydrological events.

Bridge Scour Criticality Data

FHWA's Guidance on Applying Risk-Based, Data Driven Decision-Making Process to the FHWA Scour Program explains how NBI items and related data can be used for a data-driven, risk-based scour-prevention program.[9] The FHWA direction says characteristics for prioritization may include, but not be limited to, the following:

- Functional classification
- Average daily traffic
- Emergency service needs
- Community connectivity or evacuation and recovery needs
- The cost of scour countermeasures compared to replacement cost
- The structure's remaining service life
- Funded replacement schedules

Seismic Vulnerability and Retrofit Data

FHWA's seismic retrofitting manual notes that ground motions large enough to cause damage have a 10-percent chance of occurring within the next 50 years in 37 of the 50 States.[10] The manual describes the type of risk-based analysis and decision-making that leads to investment strategies to make structures resilient. These include:

- Identifying bridges at risk
- Evaluating their vulnerability
- Initiating a program to reduce the risk

The type of decisions FHWA's retrofit manual recommends are similar to other decisions a TAMP includes. The FHWA manual recommends classifying structures as "essential" or "standard." Essential structures provide access to emergency services, have major economic impacts, are formally identified in an emergency plan, or serve a critical security link. The manual recommends risk analysis to evaluate threats and vulnerabilities. It also recommends prioritizing investments to maximize results with limited dollars.

Resilience Pilot Studies Related to Structures

Examples of the diversity of resilience threats to structures and other assets are evident in the many FHWA-sponsored resilience pilot projects. Just a few examples of how State DOTs are considering bridge conditions and characteristics to increase resilience include:

- The Massachusetts DOT developed a method for assessing vulnerable stream crossings.[11] It also conducted, with FHWA, support an analysis of the vulnerability of the I–93 Central Artery/Tunnel to sea level rise and extreme storm events.
- MnDOT assessed and ranked the vulnerability of bridges and other assets to flash floods.[12]
- Using NBI and hydrologic data, the Kentucky Transportation Cabinet (KYTC) developed a Bridge Culvert Sensitivity Index score for each bridge and culvert.[13] The analysis combined NBI condition data with data on each structure's geomorphic sensitivity, and

its criticality to the highway network. The rating of each structure can factor into KYTC's bridge investment prioritization.

Highways in the River Environment

The 2016 FHWA publication titled, "Highways in the River Environment- Floodplains, Extreme Events, Risk and Resilience," provides technical information and methods for assessing the nexus of riverine environments and transportation facilities as it relates to floods, floodplain policies, extreme events, climate change, risks, and resilience.[14] It focuses on quantifying exposure to extreme flood events considering climate change and other sources of nonstationarity. There are multiple uses for this publication, including risk and vulnerability assessments, planning activities, and design procedure development.

In discussing how to reduce the vulnerability of assets in a river environment, the publication states that planners and designers can reduce vulnerability by either reducing the sensitivity of assets to extreme events or by enhancing their adaptive capacity.[15] Among its recommendations relevant to TAMPs are to identify and prioritize critical assets based on their size, vulnerability, and how hydrological conditions have changed since the assets were designed.

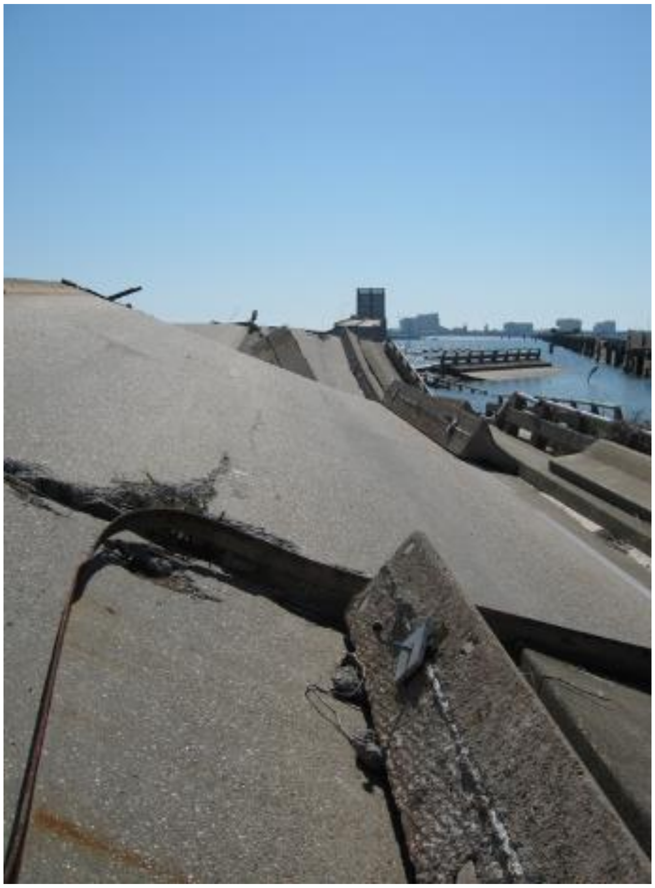
The Need for Individual State Bridge Analysis

Few studies exist that comprehensively summarized all U.S. bridge failures and documented their cause other than for seismic events. A frequently cited study is from 2003 and examined 500 bridge failures between 1989 and 2000.[16] Although bridge failures are rare, the data illustrate how closely linked failures are to extreme hydrological events. For example, the study found that 1993 experienced above-average failures with a total of 112 bridge failures. Flooding caused 75 of the 112 illustrating the effect of extreme hydrological events.

Despite the seriousness of any bridge collapse, the 500 that failed resulted in 76 fatalities over 12 years. That compares to 36,096 total highway fatalities in 2019 alone.[17]

If a study of bridge failure were updated, it is likely to document many more failures since 2000 because of the number of extreme weather events. Hurricane Maria on September 6, 2017, damaged 388 Puerto Rico bridges.[18] In 2011, Tropical Storm Irene damaged more than 300 Vermont bridges.[19] A 2013 Colorado flood damaged 120 bridges, although most did not result in failure.[20]

A study of 44 bridges damaged by 2005's Hurricane Katrina found that storm surge elevation was a primary cause of bridge damage.[21] Much of the damage was to the superstructures. Primary causes were the unseating or drifting of decks and failure of bridge parapets due to storm surge (Figure 17). Bridge inspections showed that the superstructure damage largely depended upon the connection type between decks and bents. Features associated with tropical storm Irene's bridge failures included stream power, watershed soil types, channel rating, and waterway adequacy.[22]



Source: iStock.

Figure 17. Photo. A bridge damaged by Hurricane Katrina's wave action.

A review of the literature and of the many FHWA resilience pilots do not reveal a few key condition measures that can be monitored to ensure bridges are resilient. One of the few studies on bridge failures found that even a one-year-old bridge failed during one storm event. [23] Bridge scour vulnerability is an obvious storm-related consideration. However, none of the recent research concluded that poor scour conditions alone were a primary pre-existing condition to bridge failures. Instead, factors such as stream flow, soils, storm intensity, and geomorphology were more common factors.

An NCHRP domestic scan documented how States use many measures to assess and then reduce scour risk.[24] The study did not indicate that a few performance measures or criteria were common to the 17 States studied. The study concluded that prioritizing scour efforts require a multi-disciplinary effort. It recommended States form interdisciplinary scour committees to develop risk-based scour investment strategies.

Pavement Condition, Performance, and Resilience in a Changing Climate

In an earlier section, this document summarized the importance of good pavement conditions to performance. Good pavements contribute to safety, noise reduction, and reduced operating costs. A growing body of research examines the link between a changing climate and pavement performance. The research findings did not indicate that pavements in good condition enhance resilience. The research indicated that resilience may be enhanced by elevated roadbeds, enhanced embankments, drainage structures, improved pavement designs, and other roadway features.[25] However, the research did not indicate that the pavement surface itself enhances resilience.

Instead, the research identified ways in which climate change could deteriorate pavements. Research also examined ways in which pavement strategies may need to change to sustain an SOGR.

U.S. and international research[26,27,28,29] identified many ways in which the temperature and precipitation extremes of climate change can affect pavements, including:

- Soil instability, ground movement, and slope instability leading to road damage
- In colder climates, higher temperatures could lead to more spring-like conditions that lengthen the season for frost heave and thaw-weakening.
- In warmer climates, higher temperatures could increase flexible pavement rutting and shoving and require new binders. Rigid pavements could experience more temperature-related curling and warping, greater thermal expansion and shrinkage, and more “blow ups.”
- Flooding can block roads but also weaken pavements.
- Increased freeze-thaw cycles in some locations will increase thermal fatigue.

Recent research has shown how important climate assumptions are to pavement design success. The Long-Term Pavement Performance Program (LTPP) research found that 36 percent of the damage to flexible pavements was related to subgrade and climate variables.[30] For rigid pavements, 24 percent of total damage was related to subgrade and climate variables.

Source: iStock.

Figure 18. Photo. Roadway flooding.

Complicating pavement-resilience efforts is the highly variable environmental effects (Figure 18). Environmental impacts to pavements varied by type of pavement, thickness, soil types, and pavement designs. Changes in climate that increased some damage may have decreased other types of damage, or been insignificant. Just one of many examples cited was that higher temperatures were associated with increased transverse fatigue cracking on jointed portland concrete pavement. However, increased temperatures and a warmer climate were associated with less transverse joint spalling. An increase in precipitation increased fatigue cracking on thin asphalt pavements, but not on thicker ones.

One FHWA-sponsored extreme weather pilot study by the Texas DOT demonstrated the complexity of determining how hurricanes and flooding affect pavements.[31] The Texas study found differing flooding effects depending on pavement design. Asphalt pavements of 2 inches or less without treated subgrades were vulnerable to damage, particularly if there is heavy traffic, as was experienced in Texas during flood response. Sections with 4 inches of asphalt showed no immediate flooding effect. However, if the pavement was older than 10 years, it experienced a 1-year shorter service life. A simulation also showed that when floods occur in 3 consecutive years, the service life of the 4-inch pavement is reduced from 24 years to 21 years.

New Hampshire researchers found that climate change is impacting pavements in unexpected ways. For example, sea level rise and storm surges were obvious pavement-condition threats. Additionally, researchers in New Hampshire found that sea level-driven groundwater rise will occur three to four times farther inland than surface-water flooding.[32] The research concluded that rising ground water levels threaten pavements' unbound underlying layers. Unmitigated, a two-lane road could experience a pavement-life reduction of 90 percent by 2030. While a 4-lane road could experience a 45-percent pavement-life reduction by 2060. However, relatively simple structural modifications to the pavement base and asphalt layers could eliminate 80 percent to 90 percent of the service life reduction projected with a 1-foot sea level rise.

Researchers frequently cited the difficulty pavement designers will have in identifying realistic future environmental assumptions.[33,34,35,36] For decades, pavement engineers based designs on past climatic data. As weather patterns change at an increasing rate, more uncertainty enters pavement-design decisions. One group of researchers examined 799 locations where pavements were designed using historic temperature data.[37] The researchers found that current temperature extremes were greater than assumed in the historic record. As a result, they estimated that 35 percent of the observed asphalt pavements were built with binders insufficient to perform in current temperature extremes. They estimated those pavements designed to last 20 years will require rehabilitation after 16 years when the pavement binder grade needed is wrong by 6 degrees Celsius.

Designers will need to update assumptions about temperature and precipitation extremes, flooding, fires, and other climate-induced changes. The MOT SHA plans to capture pavement-inundation data to better calibrate its pavement management system.[38] The additional data should allow its Office of Materials Technology to systematically factor flood risk into the LCP decisions.

Some changes could be project-specific or addressed through material specifications, such as improved binders.[39,40] While costs may rise, at least one study found that a change in binders to offset higher temperatures could improve pavement performance.[41] The binder change was forecast to reduce IRI by up to 5 percent and rutting up to 14 percent. Such a change would represent a project-level design decision that could have system-wide impacts important to the TAMP.

Other climate-mitigation strategies could be more expensive and require program-wide funding that could influence TAMP investment strategies. Examples of these could include elevating or otherwise "hardening" coastal roads subject to frequent inundation. The Texas study recommended adopting for flood-prone areas a more robust pavement structure. The more robust pavement could increase costs and influence the amount needed for the pavement investment strategies.

Further complicating decisions on how to increase pavement performance in the face of a changing climate is the question of timing.[42,43,44] Some research indicates most climate change impacts will occur gradually over 40 years or more. The short-term impacts may not be significant enough to influence a pavement designed for 20 or 30 years. One study using the Mechanistic-Empirical Pavement Design Guide determined that adaptive pavement strategies will be needed after 2050.[45]

Other research infers more rapid impacts. One study suggests that incremental warming will gradually shorten the winter and increase spring and late-summer conditions for some New Hampshire coastal pavements.[46] Changing season duration increases the spring-like months when pavements are most vulnerable to rutting. The study indicated the incremental impacts will steadily increase and shorten pavement life well before 2050. Short-term mitigation strategies include a 7 percent increase in pavement thickness in the early 21st century, increasing to 32-percent thickness increases by late mid-century.

One way to better understand how the future climate will affect pavements is through multidisciplinary teams.[47,48] Team members can bring updated climate data and share it with pavement designers, pavement management staff, maintenance staff, and staff who develop TAMPs. FHWA's many resilience pilots include multiple examples of how teams of stakeholders developed extreme weather response strategies.

Those reports are available at:
https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/.

The climate-response strategies can be included in each TAMP update. The TAMP could include discussion of:

- Pavements that are most vulnerable to climate threats
- Pavement lifecycle strategies that incorporate climate changes
- Risks to good pavement performance presented by extreme weather events
- Pavement investment strategies that accommodate resilience efforts

CHAPTER 6. THE LINKAGE BETWEEN DRAINAGE STATE OF GOOD REPAIR AND PERFORMANCE

The critical path to long-term performance for pavements, safety, and environmental enhancement may well include good drainage performance. The control, or lack of control, of water affects long-term pavement performance (Figure 19). Excess amounts of water can contribute to hydroplaning and even sweeping vehicles off roadways. Water quality is affected by how, and how slowly, water drains from roadways.

Source: iStock.

Figure 19. Photo. A pothole full of water.

Managing drainage assets is not required under the performance management regulation of 23 CFR Part 490 or the asset management regulation in 23 CFR Part 515. However, the importance of good drainage to highway performance is increasingly recognized. It is likely that more and more State DOTs will increase the sophistication of their drainage management to enhance highway performance.

In 2002, an NCHRP synthesis study indicated that no State that responded to a survey reported it had a comprehensive culvert-management system.[1] By 2007, however, an FHWA survey indicated that at least 29 States had some form of culvert management system.[2] In 2019, at least three States included culverts in their TAMPs; those were California, Minnesota, and Ohio. An Internet search finds State DOTs in Wisconsin, Vermont, Maine, and others enhancing their drainage inventories.

Drainage and Pavement Performance

The linkage between good drainage and transportation performance has been long understood. Early pavement designer John L. McAdam emphasized the importance of good drainage to roadway performance in a series of reports he produced between 1816 and 1820[3,4] Eighteen-hundred years before McAdam, the Romans included drainage ditches and pavement slopes to prevent water from weakening their roads.[5] An old cliché is that three things matter to pavement performance, “drainage, drainage, and drainage.”[6]

Recent research confirmed these long-recognized benefits and enhanced them with new insights. One recent study confirmed anew the understanding that the strength of a pavement base measured by the resilient modulus dropped significantly with base saturation.[7] The deterioration was negligible in dry-freeze conditions but substantial in wet-freeze ones.

Pavement designers incorporate estimated amounts of moisture into their pavement design. Several of the researchers, however, state the problem is that many States lack a "follow through" drainage maintenance process. The lack of a maintenance process based upon the pavement designer's assumptions can lead to early pavement failure. Researchers documented many studies such as the early AASHTO Road Test that confirmed moisture's role in pavement deterioration.[8]

A Minnesota DOT subsurface drainage manual states subsurface drainage maintenance is essential to protecting pavement investments and performance.[9] It states that not only is the capital cost of the drainage structures at risk from poor maintenance, but the pavement is, as well. It states that moisture damage to pavement can be several times more costly than drainage maintenance.

The Minnesota subsurface drainage manual alludes to a point made several times in FHWA asset management publications—that multidisciplinary, cross-cutting coordination is needed to preserve assets. The Minnesota manual notes when describing drainage maintenance needs that both pavement designers and maintenance staff must coordinate. The manual states that pavement designers well understand the importance of drainage maintenance. However, they do not direct the maintenance staff who are needed to annually inspect and clear drainage structures.[10]

As early as 1997, an NCHRP drainage maintenance synthesis report recommended a team approach. Otherwise, drainage failures can compromise pavement performance.[11] It noted that pavement designers, construction staff, and maintenance staff need to coordinate for pavements to not fail prematurely from poor drainage. Examples of needed cross-coordination include:

- The designer must know if, or if not, drainage maintenance will occur and to what degree. The amount of pavement base moisture is an important design consideration. If the designer assumes frequent drainage maintenance occurs, and it does not, the design could be flawed.
- Construction crews must understand the details of the permeable base, edge drains, and other features to ensure they are constructed to perform as intended.
- The maintenance staff must understand how and when drainage maintenance needs to occur.
- A "feedback loop" from maintenance to design could include advice on how to construct and mark outlets so maintenance staff can easily find them.

Further evidence of the benefits of cross-cutting, interagency coordination was included in the drainage research.[12] Not only does drainage maintenance extend pavement life by controlling base moisture, so does pavement preventive maintenance. Crack sealing and various seal coats reduce surface moisture reaching pavement bases.[13,14] Researchers noted that long-term pavement performance can be enhanced by preventive maintenance that reduces surface water infiltration. Those efforts are complemented by regular sub-surface drainage maintenance.

Several studies note that water reaches pavement structures through pavement cracks, side ditches, melting ice layers during spring thaws, from the water table, and from water vapor.[15,16]

Recent New Zealand research confirmed that enhanced drainage maintenance could be a cost-effective means to extend pavement life.[17] The project modeled different degrees of drainage obstruction, such as the effect of a 20-percent blockage or a 100-percent blockage. It determined that weeks could pass after rainfall before the base returns to equilibrium condition when drainage is even partially blocked. In the meantime, significant pavement damage can occur. The study recommended prioritizing drainage maintenance as a cost-effective pavement strategy. Emphasis can be in areas with high water tables or other hydrologic risks.

Research continues into the effect of climate-induced moisture changes and pavement performance. One study noted a sharp divide in the way climatologists and pavement designers face climate forecasts.[18] Climatologists emphasize probabilities. Pavement designers rely on “known” and “best available” data. That study recommended more recognition of the hydrological uncertainty that factors into long-term pavement designs. Changes in precipitation rates, freeze-thaw cycles, and subsurface moisture could affect how drainage and pavement performance are addressed.

Another study made similar points. It recommended consideration for how climate-induced precipitation changes may require additional drainage strategies to ensure flexible pavement performance.[19] It noted that when flooding becomes more frequent, unbound layers and subgrade stiffness is reduced. Higher roadways, enhanced drainage, and reduced use of fine materials in unbound layers may be needed.

NCHRP Synthesis 239[20] summarizes decades of research on the linkage between good drainage design and maintenance and pavement performance:

> *“Subsurface drainage is a key element in the design of pavement systems. Indiscriminate exclusion of this element will assuredly lead to the premature failure of pavement systems, thereby resulting in high lifecycle costs. Faulting and associated pumping in rigid pavement systems, extensive cracking from loss of subgrade support in flexible pavement systems, and distress from significant frost heave are clear signs of inadequate drainage. After years of unsuccessful sealing attempts, we have learned that we cannot prevent water from entering a pavement and that the removal of that water is essential for the pavement elements to perform as predicted.”*

Drainage and Safety Performance

The effects of pavement friction and rutting on highway safety has been discussed in earlier sections of this report. The degree to which friction and rutting influence safety is, in part, influenced by drainage. Well-functioning drainage removes water from roadway surfaces more quickly and can contribute to highway safety.[21]

FHWA’s guide, Maintenance of Drainage Features for Safety, identifies several ways in which good drainage contributes to safe roadways.

Over time, traffic and resurfacings can affect the original cross slope of roadways. The lack of adequate cross slope can exacerbate ponding in ruts and other pavement depressions. The ponding decreases pavement friction and can cause motorists and bicyclists to swerve to avoid the water. Ponding also can increase when storm drains are blocked or nonexistent.

The degree to which water collects in ruts also can be influenced by the effectiveness of drainage. Water is less likely to remain in ruts if adequate drainage is designed and drainage features are functioning.

Source: iStock.

Figure 20. Photo. Tire splash.

In sections of the travel way where runoff flows directly onto the shoulders (where there are no curb and/or gutters), water may collect along the edge of the travel way. Water on a portion of roadway can result in drivers losing control of their motor vehicle, particularly when braking in an emergency. This can happen when the inside tires are in contact with roadway surface while the braking ability of the outside tires is hindered by the water (Figure 20).

Water ponding on the edge of the pavement contributes to the deterioration of the pavement edge and the rutting of stabilized soil supporting the pavement edge. That can result in additional safety hazards. Edge drop-offs and shoulder scour are often caused when water is trapped at the pavement edge by the build-up of debris and vegetation growth. Traversable, well-maintained roadside ditches both reduce the chance of roll over crashes and reduce water on the roadway.

Drainage maintenance is not only important for pavement performance but also safety performance. Drain inlets or outlets clogged with vegetation or litter can cause roadway ponding.

Grates and drop inlets can be safe for motorists but can be hazardous for bicyclists. The amount of bicycle and pedestrian traffic should influence drainage structure design.

Drainage and Water Quality

Well-maintained drainage may not only enhance safety, condition, and pavement performance, it can also enhance the environment when best management practices (BMPs) are applied.[22] TAMPs could acknowledge that their investment strategies support good drainage for several reasons. First, it helps minimize deterioration of pavements. Second, investment strategies that improve water quality support progress toward the national goals. One of the seven national transportation goals is environmental sustainability, "[t]o enhance the performance of the transportation system while protecting and enhancing the natural environment."[23] Supporting water quality could also support the agency's mission or vision, which often includes enhancing the environment. TAMP objectives should align with the State DOT's mission.[24] The MOT SHA vision statement says, "To provide a safe, well-maintained, reliable highway system that enables mobility choices for all customers and supports Maryland's communities, economy, and environment."[25] The Florida Department of Transportation mission is as follows: "The department will provide a safe transportation system that ensures the mobility of people and goods, enhances economic prosperity, and preserves the quality of our environment and communities."[26] The Colorado Department of Transportation vision is, "To enhance the quality of life and the environment of the citizens of Colorado by creating an integrated transportation system that focuses on safely moving people and goods by offering convenient linkages among modal choices." [27] Additionally, drainage investments can extend pavement life and reduce crashes while reducing highways environmental impacts. Poorly maintained culverts (Figure 21) can lead to flooding and collapse during storm events.

The U.S. Environmental Protection Agency notes that heavy metals, oils, and other pollutants can exist in highway runoff. Drainage BMPs can prevent erosion that carries these materials and also can trap pollutants before they can be discharged.[28] Additionally, controlling the speed and flow of highway runoff can reduce harmful stream erosion.

Source: iStock.

Figure 21. Photo. A deteriorated culvert.

The FHWA Hydraulic Engineering Circular 22 notes that storm water BMPs are usually based on three types. One type reduces erosion, another prevents mixing of pollutants from construction sites with storm water, and a third traps pollutants before they are discharged. Many strategies are used in these BMPs. Just a few include roadside swales, detention/retention facilities, infiltration basins, sand filters, and vegetated areas. Even wetlands can be part of a BMP.

As with drainage overall, ongoing maintenance is essential for the long-term contribution of the highway BMPs to water quality.[29] The FHWA circular states that even in a properly designed and constructed storm drainage system, a comprehensive program for storm drain maintenance is essential. Regular in-pipe inspection will detail long-term changes and will point out needed maintenance. The program should include periodic inspections with supplemental inspections following storm events.

CHAPTER 7. STATE OF GOOD REPAIR AND COMPLETE STREETS

When using lifecycle plans, State DOTs periodically rehabilitate or reconstruct urban pavements and bridges. When urban pavements are reconstructed, projects often replace pavement bases, update underground utilities, and rebuild drainage, including curbs and gutters. For an individual roadway segment, these types of projects may occur only every 30 to 50 years. However, with thousands of urban lane miles, State DOTs may be involved in several such projects annually.

These urban reconstruction projects provide opportunities for coordinating Complete Street projects with pavement and bridge LCP (Figure 22). Complete Street projects support multiple performance objectives including enhancing bicyclists and pedestrian safety, supporting Active Transportation, supporting transit, and complementing MPO objectives. These projects may provide the least-cost opportunities for adding sidewalks, bike lanes, streetscaping, and related attributes. The pavement reconstruction project already includes costs for contractor mobilization, maintenance of traffic, and drainage repairs. Opportunities exist to cost share with transit, safety, and other programs to implement Complete Street concepts with such reconstruction projects.

Source: iStock.

Figure 22. Photo. A pedestrian crossing.

FHWA defines Complete Streets as being designed and operated to enable safe use and support mobility for all users.[1] A Complete Street could include many elements, including sidewalks, bike lanes, bus lanes, public transportation stops, crossing opportunities, medians, curb extensions, and landscaping.

When considering how long-term pavement conditions affect overall system performance, a State DOT could evaluate the following opportunities to achieve the agency’s mission, support the national goals, and deliver needed pavement-reconstruction projects:

- Do urban pavement rehabilitation and reconstruction projects provide opportunities to reduce bicyclist and pedestrian crashes by including medians, pedestrian islands, and other features?
- Can transit and Active Transportation opportunities be enhanced with project elements?
- Can the urban environment be enhanced by the appearance, color, textures, and features included in the reconstruction project which supports the agency’s “quality of life” objectives?

The ARC identified three priorities for safer walking and bicycling.[2] First, too many people are killed walking and cycling. Second, roadway design is the foundation of traffic safety, but safe design is unevenly distributed, particularly for underserved communities. Third, the fear of being struck is a major barrier to increased walking, biking, and use of transit. Its plan calls for a Safe System approach to urban and suburban roadways and the long-term integration of Complete Streets into transportation projects. ARC describes Safe Streets as a holistic, systems-based strategy that: accounts for all roadway users; anticipates that humans will make mistakes; and shares responsibility for safety between individual road users and system designers. ARC identified a reconstruction project as a potential opportunity to improve system performance in this capacity.

The ARC Safe Streets for Walking and Bicycling plan states in part:

> "*Each year, hundreds of roadway projects in the 20-county region rebuild existing roads or build new ones. New urban and suburban development continues in one of the fastest growing regions in the country. Every one of these projects is an opportunity to implement proven safety countermeasures or change communities to those that support complete streets and eliminate fatal and serious injury crashes among all road users.*"[3]

Urban reconstruction projects that implement lifecycle strategies not only align with the TAMP's lifecycle strategies, but they can also integrate into the metropolitan planning process by supporting MPO objectives. For example, "promote the redevelopment of declining and abandoned areas" and "promote healthy and active living" are two objectives of the greater Cleveland MPO that could be supported with Complete Street projects.[4] Objectives like these can provide opportunities for TAM on pavement and bridges to support.

The Denver Regional Council of Governments' (DRCOGs') Active Transportation Plan states that pedestrians and bicyclists are the most vulnerable road users.[5] Its Active Transportation Plan noted that only 5 percent of respondents felt comfortable bicycling on a four-lane facility, while 72 percent would be comfortable bicycling on a four-lane facility with a separated bicycle lane. The DRCOG's Active Transportation Plan lists among the benefits of Active Transportation improved health, improved accessibility for people with disabilities, improved safety, and increased economic vitality. One way this was accomplished was by leveraging opportunities through private development, public utilities projects, and major roadway projects to construct or reconstruct sidewalks and to build new bikeways in order to close network gaps in sidewalks and bikeways.[6] Other opportunity is in roadway resurfacing projects. Such projects are a cost-effective opportunity to add bicycle facilities and upgrade curb ramps.[7]

Earlier sections of this document discussed the importance of Complete Street-like improvements to reverse the trend of rising pedestrian fatalities. Many Complete Street elements have been proven through CMFs to reduce pedestrian injuries and deaths. One study attributed up to 3,500 reduced pedestrian and bicyclists deaths over 29 years to Florida's Complete Street program.[8] Another study noted Germany's pedestrian-fatality rate was one-fifth that of the U.S. rate, largely because of more pedestrian-friendly German urban streets.[9] These and other studies appeared to show a direct link between Complete Street-type of improvements and reductions in pedestrian and bicyclist fatalities.

Complete Streets include elements that one comprehensive study found improved pedestrian safety.[10] Those elements are:

- Separation of pedestrians from vehicles by time or space
- Increased pedestrian visibility
- Reduced vehicle speeds

Elements such as pedestrian islands, medians, and signal timing favoring pedestrians provide both spatial and temporal pedestrian-vehicle separation. Enhanced lighting and warning at crosswalks enhance pedestrian visibility. Traffic calming reduces speeds, which can reduce both pedestrian crash numbers and severity.

CHAPTER 8. STATE OF GOOD REPAIR AND MOBILITY AND RELIABILITY

Although it would seem intuitive that conditions, particularly pavement conditions, would affect travel speed or reliability, a literature review for this publication did not produce evidence of links between pavement conditions and reliability. Some research found correlation between pavement conditions and travel speed, but the results were mixed.

One 2013 study[1] noted a lack of recent research on the link between IRI and travel speed, with most of the research pre-dating the 2000s. This study used roadway data from the California Department of Transportation (Caltrans) and found a slight effect on travel speeds based upon a section's IRI. The regression model developed from the research indicates that the average speed decreased by 0.0083 miles per hour for each inch that the IRI increased.

A 1996 research paper from the Swedish National Road Administration found a 1-mph speed increase between a set of newly resurfaced roads and a control group of similar roads with poor pavement conditions. A 1992 research paper[2] found a reduction in passenger car speed when IRI and RD increased.

A case study in India[3] on the influence of pavement distress on average travel speed showed that the average speed was significantly reduced with the increase of pavement distress level. The study found that PCI had greater correlation to travel speed than did shoulder width or traffic flow.

A similar correlation was found between pavement condition with average speed and headway in a study of pavement condition and road grade in thirteen road segments in the Harbin City of China.[4] The study evaluated pavement condition based on potholes' width, RD, crack ratio, and gap repair ratio. Another study found that severely distressed pavement conditions could result in capacity reduction by up to 30 percent.[5] It concluded that the influence was statistically significant. However, this study considered only "with distress" and "without distress" conditions and did not account for the degree of distress.

In summary, the current literature found some correlation between pavement conditions and travel speed, but often, the effects were not very pronounced.

Although the connection between IRI and travel speed may not appear to be robust, the connection between IRI and comfort has been documented. Intuitively, it would seem obvious that speeds and driver satisfaction would be lower when pavements are in poor condition.

Several researchers suggested that IRI thresholds be set based on a roadway's travel speed.[6,7,8] This is because at low speeds, drivers rate a higher IRI, or more roughness, to be acceptable. But as speed increases, so does the "jolt" from rough pavement and the comfort or quality of ride decreases.

At least one paper[9] also recommends a speed-based threshold for rutting. It concluded that when speeds are above 74 mph (120 kilometers per hour), a RD of .4 inches (10 millimeters) under wet conditions can make lateral skid conditions unsafe. However, the study found that speeds below 50 mph were less affected by the RD of .4 inches. The FHWA rutting performance measure considers rutting of greater than .4 inches to be rated as poor.[10]

Disruption of travel time reliability is associated with uncertainty or disturbance of normal operating conditions by nonrecurring events, and hence, unpredictable to drivers. The primary ways pavement and bridge conditions affect travel time reliability are through safety impacts and traffic disturbance caused by work zones.[11] The delay caused by traffic incidents is associated with unreliability because accidents are non-recurring. Previous sections showed that the infrastructure conditions, especially pavement conditions, have significant safety impacts, influencing the rate of crashes and other incidents.

The amount of delay caused by the work zone depends primarily on the lane availability, pavement condition, presence of people, presence of law enforcement on or around the work zone, type of operation and the equipment, work-zone length, and duration of the work. Lane availability may be changed by the work zone in the form of lane closure, lane width reduction, or changes in lane configuration.[12] The traffic disruptions caused by work zones can have adverse effects on the safety and mobility, not only along the road segment accommodating the work zone, but across the road network. In addition, allowing assets to downgrade to a lower condition state can also impact the duration and extent of the future maintenance operations. Delayed maintenance leads to costlier, more intensive repair or rehabilitation operations associated with longer downtime of the road segment and higher levels of traffic disruption.[13] In other words, these reports indicate that timely maintenance of pavements and bridges not only reduces the cost of maintenance, but also makes it easier to keep the traffic disruption at a minimum.

Asset management is playing an increasingly important role in keeping Transportation Systems Management and Operations (TSMO) assets in good repair to support mobility and reliability. Five State DOTs included mobility or reliability-related assets in the 2019 TAMPs. The Connecticut DOT's 2019 TAMP included traffic signals, signs, sign supports, and pavement markings. The Minnesota DOT's 2019 TAMP included overhead sign structures, high-mast light towers, traffic signals, lighting, and Intelligent Transportation (ITS) assets. The UDOT TAMP described UDOT's management of advanced traffic management systems (ATMS). The Caltrans TAMP included transportation management system (TMS) assets. The Nevada Department of Transportation included ITS assets.

A common theme in the literature about asset management and TSMO assets is that the systems included many complex electronic and software components, all of which require different lifecycle strategies.[14,15] Each agency may have different components, from different manufacturers, of different ages, all of which require agency-specific management processes.

To help States keep TSMO assets in good repair to support mobility and reliability, FHWA has produced a primer called "Applying Transportation Asset Management" to ITSs[16] and another on traffic signals. The primers are structured around five emerging themes in ITS and traffic signals asset management in line with the TAMP requirements. They are:

- **Asset Identification**—This theme provides an overview of the type of asset information agencies should be collecting for ITS and signals assets and why.
- **Management Systems for Assets**—This theme discusses management systems in terms of a collection of processes, procedures, tools, or software systems to help an agency

collect and store information while providing analysis to inform asset management decision-making.

- **Performance Measures and Targets**—This theme highlights some of the practices that agencies can adopt to measure the condition of ITS and traffic signal assets, as well as establishing targets. This acknowledges the variety of different components with different life expectancies and conditions, which can lead to uncertainty about how to best define the overall condition.
- **Maximizing Performance**—This theme looks at best practices for planning and maintaining ITS and traffic signal assets in terms of estimating the cost of managing an asset class, or asset subgroup, over its whole life, with consideration for minimizing cost while preserving or improving the condition. This includes adopting long-term maintenance plans and considering lifecycle analysis for ITS assets and considering a plan for when such assets may become obsolete or no longer supported.
- **Resource Allocation**—This theme looks at recommended approaches for identifying and communicating funding and resource needs for long-term management of ITS and traffic signal assets.

Maintaining TSMO assets in good repair becomes a critical issue as these systems age.[17] Systems plagued by bugs and inoperable components will not only fail to support mobility, but they can also reduce the perceived utility of the systems. The FHWA primers reiterates earlier research[18,19] that recommends State DOTs develop investment strategies so that TSMO assets can remain in good repair to support mobility and reliability.

CHAPTER 9. LINKING TAMPS TO MULTIPLE PERFORMANCE AREAS

After discussing how assets in good repair can support multiple performance areas, this document shifts to discussing how the TAMP-development process could incorporate considerations of bridge and pavement contributions to multiple performance areas. Then, it will discuss how each TAMP section could contribute to understanding how the TAMP supports these multiple objectives.

Incorporating Multiple Perspectives into a TAMP

In a TAMP question and answer guidance document,[1] FHWA stated:

> "*State DOTs are required to have a process for analyzing gaps in the performance of the NHS that affect NHS pavements and bridges regardless of their physical condition (23 CFR 515.7(a)(2)). Under this provision, State DOTs must address instances where the results or recommendations from other plans, including the State's Highway Safety Improvement Program, State Freight Plan, etc., may have an effect on NHS pavement and bridge assets. This could occur if the recommendations from the other plans call for additions or changes to the existing pavements, bridges, or other physical assets.*"

In the preamble to 23 CFR Part 515,[2] FHWA also noted that information on changes needed to NHS pavement and bridge assets to support system performance can be gathered by reviewing other State plans. These could include the HSIP, SHSP, and the State Freight Plan, if the State has one. Other relevant plans and programs could be the LRSTP, the MTP, or State or regional efforts for TSMO.

Further linkage of the TAMP to other objectives comes from provisions of both 23 CFR Part 450 and 23 CFR 515.9(h).[3] The TAMP provision at 23 CFR 515.9(h) requires the State DOT to integrate its asset management plan into its statewide transportation planning processes. The planning provision at 23 CFR 450.206(c)(4) requires the State DOT to integrate into the statewide transportation planning process, directly or indirectly, the goals, objectives, performance measures, and targets of other State transportation plans, such as the TAMP. These provisions mean that, in carrying out the transportation planning process, the State DOT must consider its TAMP, including the TAMP's investment strategies, as part of the decision-making process during planning.

The coordination of the TAMP with other plans and programs could occur in multiple ways, including:

- Staff who develop the TAMP could review other plans and programs and look for opportunities to coordinate TAMP components with those plans and programs.
- TAMP staff could convene multidisciplinary working groups to develop the TAMP. Members could represent those who develop the LRSTP, SHSP, HSIP, MTPs, or the Freight Plans. The working group could identify links between the TAMP and the other plans.
- Because congestion reduction and environmental sustainability are goals, staff who work in those areas could provide input to the TAMP.

- State DOTs could coordinate with MPOs about how the TAMP investment strategies could link bridge and pavement programs to regional and community objectives.

How Each TAMP Section Could Reflect Performance Considerations

A TAMP shall discuss how the plan's investment strategies collectively would make or support progress toward achieving national goals[4] identified in 23 U.S.C. 150(b).[5] As noted, the national goals are broad. They encompass safety, infrastructure condition, congestion reduction, system reliability, freight movement and economic vitality, environmental streamlining, and reduced project delays. Investment strategies result from the components or analysis of each TAMP section. Each TAMP section could help "set the stage" for investment strategies that support multiple performance objectives and the seven national goals.

Per 23 CFR 515.9(d), TAMPs asset management plans shall include:

- Asset management objectives that should align with the State DOT's mission and must be consistent with the purpose of asset management
- Asset management measures and targets for asset condition including those established pursuant to 23 U.S.C. 150 for NHS pavements and bridges; the State DOT may include measures and targets for NHS pavements and bridges established through pre-existing management efforts or through new efforts
- A summary description of the condition of NHS pavements and bridges regardless of ownership
- Performance gap identification. Performance gaps are, "the gaps between the current asset condition and State DOT targets for asset condition, and the gaps in system performance effectiveness that are best addressed by improving the physical assets."[6]
- LCP
- Risk management analysis
- Financial plan

An asset management plan shall discuss per 23 CFR 515.9(f) how the plan's investment strategies collectively would make or support progress toward:

- Achieving and sustaining the desired SOGR over the life cycle of assets
- Improving or preserving the condition and performance of the NHS relating to physical assets
- Achieving the State DOT targets for asset condition and performance of the NHS in accordance with 23 U.S.C.150(d)
- Achieving the national goals identified in 23 U.S.C. 150(b)

A State DOT must include in its plan per 23 CFR 515.9(g) a description of how the analyses required by State processes developed in accordance with section 515.7 (such as analyses pertaining to life cycle planning, risk management, and performance gaps) support the State DOT's asset management plan investment strategies.

Performance-Related Objectives, Measures, and Targets

TAMP objectives could include consideration of multiple performance areas. For example, pavement objectives could include language to support safety, such as ensuring that pavements have adequate friction in the appropriate locations to support the SHSP and HSIP. Objectives could reference that the State DOT will manage pavements to reduce rutting, if wet-weather crashes are a focus of its highway safety efforts. If roadway departure crashes are a priority, the pavement objectives could include language, as appropriate, to fund wider shoulders, the Safety Edge, or other complementary strategies.

Bridge objectives could indicate that the State DOT will manage bridges to ensure the long-term mobility of passengers, freight, and transit operations. Such an objective could be relevant to plans for managing the State's particularly large bridges. In many States, a few very large structures are disproportionately important to freight haulers or motorists. Long-term planning for those structures could include consideration for how they will complement long-term freight, transit, and mobility needs.

Resulting from these objectives could be pavement-related measures and targets to support them, including:

- Achieving the annual skid testing and remediation targets particularly at high-risk locations such as intersections, crosswalks, horizontal curves, or railroad crossings
- Limiting the amount of rutting, if reducing rutting is among the State DOT's crash-remediation strategies
- Systematically adding shoulder treatments to HRRRs if shoulder treatments are part of a roadway-departure-reduction strategy

Bridge-and-structure-related measures and targets could include:

- Achieving the number of seismic retrofit projects scheduled in a resilience plan
- Reducing the number of load-limited bridges that could impede freight movement
- Improving bridges that are too narrow, have inadequate geometry, or do not support Active Transportation
- Replacing or rehabilitating the number of structures deemed vulnerable to wave action, scour, or other hydrologic threats
- Progress toward completing culvert and drainage structure inventories and management programs

Summary Description of Assets and Those Affecting Performance

State DOTs could enhance the summary description of assets by summarizing the asset subgroups or collections of individual assets that are most critical to improving performance. It is likely that such assets will influence later TAMP sections, such as the lifecycle plan, risk analysis, financial plan, and investment strategies. These assets can create inordinate risks and opportunities to condition and performance, as well as to agency budgets. Examples could include:

- Large bridges in poor or nearly poor condition that, over time, could be impediments to both freight movement and achieving condition targets. Such bridges can be disproportionately influential to overall statewide conditions, to financial plans, and to freight movement.
- The urban pavements that need reconstruction and will be candidates for Complete Street improvements. Again, these locations can create disproportionate financial impacts. They are more expensive than typical resurfacings but present opportunities to enhance pedestrian safety and achieve other Complete Street objectives.
- The structures at risk from seismic or climatic affects, such as bridges vulnerable to wave action. Summarizing these types of structures draws attention to the need for resilience investments and to the threats that could impede the SOGR.
- Structures or pavements that represent "historic waves" that will reach their lifecycle's end during the 10-year TAMP period. These could include Interstate pavements and bridges that have not been reconstructed since their original construction, or they could include early-generation ITS assets that are approaching obsolescence. Overhead sign structures are another class of such assets that some State DOTs have cited as requiring systematic investment.

Condition Gaps and Their Effect on Performance

The objective of performance gap analysis is to track performance compared to short-term targets and long-term performance goals for a SOGR.[7] Also, the information from a performance gap analysis is applied to undertake life cycle and financial planning to develop alternative strategies to close or address the identified gaps to operate and improve or preserve the existing assets.

In addition to describing the gaps between conditions and short-term targets, the performance gap analysis could describe condition-related performance gaps. Examples could be:

- Gaps in pavement friction, rutting, shoulders, or other attributes that present gaps to the State DOT's highway safety strategies
- The number of urban pavement sections lacking sidewalks, bike lanes, or pedestrian features that impede the State DOT's Complete Streets, pedestrian-safety, or Safe Routes to School targets as described in Safe Routes to School Programs[8]
- The number of bridges that have not been "hardened" or retrofitted for seismic or hydrological threats according to state resilience plans or strategies
- Gaps in data, condition, or investments to understand and achieve resilience and water-quality objectives for culverts and other drainage features
- Gaps in the number of roadway sections vulnerable to flooding or sea level rise that have not yet been improved as called for in State or regional resilience plans

How Lifecycle Plans and Performance Are Linked

LCP both informs performance gap analysis for asset condition and is informed by the performance analyses for other performance areas.[9] LCP provides the strategies that determine the resources needed to achieve long-term objectives for the TAMP that may also influence other planning documents. Other plans, such as the SHSP, provide context to the LCP analysis. Those plans help the State DOT better understand how achieving the objectives and targets established in those plans impact the agency's preferred life cycle strategy for each asset.[10]

In addition to managing an asset's condition, the LCP process considers how the asset performs within the larger transportation system. LCP begins with performance objectives.[11] The objectives ensure that investments address strategic agency priorities. Asset condition and minimum acceptable performance are two examples of the type of performance measures LCP uses. Both the condition measures and the performance measures help determine when asset improvements or interventions are needed.

If the size, design, or components of a bridge or pavement do not contribute to objectives such as safety, mobility, or resilience, those considerations could influence the lifecycle plan. Assets may be retired before the end of their lifecycle to meet system performance objectives, or the asset's need for rehabilitation or reconstruction could provide the opportunity for adding features—such as Complete Street or resilience components—to maximize overall system performance, or the lifecycle preservation treatments could be timed or designed to enhance safety.

The TAMP's lifecycle plan could discuss how LCP strategies mesh with system performance objectives by:

- Discussing how preservation treatments, such as thin pavement overlays, are evaluated for their contribution to pavement performance and safety performance
- Explaining if and how rural pavement treatments are coordinated with HRRR strategies, such as improving shoulder conditions
- Illustrating how urban pavement-reconstruction or rehabilitation programs will coordinate with Complete Street efforts
- Coordinating urban bridge replacement projects with objectives for Complete Streets, Active Transportation, or Safe Routes to School
- Enhancing resilience by incorporating weather and seismic risks into bridge and pavement lifecycle plans

Enhancing Performance by Managing Risks

The risk management section could discuss which asset-condition risks threaten system performance. It also could identify the mitigation strategies the agency adopts to reduce system condition risks and enhance system-performance opportunities. Examples could include:

- Pavements threatened by periodic flooding present risks to long-term pavement performance and to mobility. Incorporating treatments to reduce these vulnerabilities could enhance both long-term pavement performance and the transportation system's resilience by reducing the likelihood that the pavement fails, or that the roadway closes during emergency events.
- Aging, deteriorating large structures can present a risk to bridge performance targets, to long-term freight mobility, and to agency budgets. Treatment or replacement plans for these bridges reduce both long-term condition risks, as well as long-term freight mobility risks.

- Pedestrian safety risks can be reduced by incorporating pedestrian-safety treatments in urban pavement projects.
- Risks to road failure during increased storm events can be reduced through culvert inventory, inspection, and maintenance programs.

Improving Performance Through Financial Plans and Investment Strategies

TAMPs' discussion of financial plans and investment strategies could articulate how the strategies both achieve condition targets and also enhance performance in multiple areas. Examples include:

- The financial plan's work type allocations for reconstruction and rehabilitation could be adequate to support the inclusion of Active Transportation or Complete Streets elements when urban pavements are reconstructed.
- The financial plan could include line items for improving at-risk assets that reduce system performance, such as load-limited bridges or aging pavements that require reconstruction.
- Rural pavement investment strategies could include funding for Safety Edges, improved shoulders where needed, or coordination with HRRRs strategies.
- Urban pavement programs are funded and linked to programs for pedestrian safety, intersection safety, or other high-risk locations.
- The financial plan includes funds for bridge investment strategies that consider not only bridge conditions but also include funds to address the need for bridges to accommodate Super Loads, long-term capacity needs, or Active Transportation needs.
- Bridge and pavement investment strategies include consideration for resilience to reduce threats from extreme weather, sea-level rise, or seismic events.
- Investment strategies prioritize high-risk assets such as aging Interstate pavements and bridges, or routes critical to emergency response.

In short, the financial plan and investment strategies could summarize how each respond to the needs, gaps, risks, and lifecycle strategies to both improve or preserve conditions and enhance system performance.

CHAPTER 10. SUMMARY AND CONCLUSION

Because each State DOT defines its own SOGR, each has broad latitude to link its performance objectives to its asset conditions. A State DOT could add pavement friction as an SOGR criterion in addition to IRI, rutting, cracking, or faulting. It could decide a pavement does not support safety performance if its shoulders are inadequate. A pavement's SOGR could consider whether its crown and cross slope quickly drain rainfall. Bridges may be in good repair if they have sidewalks and bike lanes to meet Active Transportation objectives. Pavements and bridges may be in good repair if their elevations can withstand flooding, sea level rise, or wave action. A lack of these attributes could mean the assets' condition do not support performance objectives.

Balancing efforts to enhance an asset's condition with its contribution to system performance can be complex. In earlier sections, this document described the balance necessary to make pavements long-lasting, smooth, and quiet while providing adequate friction. Financially strapped agencies may struggle to widen bridges to accommodate pedestrians and cyclists if they face declining bridge conditions. Agencies that are striving to achieve pavement targets may not easily afford the extra costs to add Complete Street elements to pavement-reconstruction projects.

The TAMP-development process provides a framework for considering these complex tradeoffs. The TAMP describes how the highway system will be managed to achieve State DOT targets for asset condition and system performance effectiveness while managing the risks, in a financially responsible manner, at a minimum practicable cost over the life cycle of its assets.

The TAMP articulates condition and performance objectives. Then it analyzes how lifecycle plans and investment strategies close the gaps and manage risks to condition and performance. The TAMP provides a framework for incorporating system performance strategies as part of asset-condition strategies.

The TAMP-development staff can coordinate stakeholders to identify opportunities for enhancing system performance while deploying lifecycle strategies. The TAMP development process can include stakeholders' perspectives for safety, mobility, resilience, freight movement, reliability, and sustainability. Each stakeholder could contribute to considerations of how bridge and pavement lifecycle plans can consider more than only asset conditions. They can consider if, how, and when asset-treatment strategies can be enhanced to achieve other performance objectives.

The TAMP also can acknowledge and incorporate the priorities of other plans. These include the SHSP, HSIP, and the state Freight Plan, among others. Also, important could be the State DOT and MPO strategies for congestion reduction, reliability, and environmental sustainability. Each plan and program comes with its own resources, including funding, data, and expertise. The TAMP can capture from these other plans and programs linkages to both support asset condition strategies and system performance strategies.

The research and examples in this report document the linkage between a SOGR and performance. The TAMP provides a means to analyze, explain, and deploy strategies to further strengthen those linkages.

APPENDIX A. FICTIONAL TAMP CHAPTERS LINKING CONDITION TO PERFORMANCE INTRODUCTION

The following appendices include three sections of a fictional TAMP. The three fictional sections are written to illustrate the concepts in an FHWA report entitled "How Pavement and Bridge Conditions Affect Transportation System Performance."[1] That report summarizes how bridges, pavements, and other assets in good condition support multiple transportation objectives, such as safety, resilience, environmental quality, and the overall quality of life. This report illustrates how a fictional State DOT could use that report's concepts to link its TAMP to a wide array of performance objectives.

The topics of these chapters are risk management, performance gap analysis, and investment strategies. The chapters are consistent with the typical State DOT TAMPs and with the 23 CFR Part 515 requirements, although representing a fictional State DOT. Of particular relevance to these chapters is the performance emphasis in 23 U.S.C. 119 (e)(1). It states, "A State shall develop a risk-based asset management plan for the NHS to improve or preserve the condition of the assets and the performance of the system." Also relevant to this document is 23 USC 119(e)(3), which states, "In developing a risk-based asset management plan, the Secretary (of Transportation) shall encourage States to include all infrastructure assets within the right-of-way corridor in such plan." These chapters illustrate just a few ways in which a fictional State DOT could link investment strategies to numerous performance objectives.

Background Relevant to These Fictional Chapters

The asset management regulation in 23 CFR Part 515 includes the following regarding performance gap analysis, risk management plan, and investment strategies:

"A State DOT shall establish a process for conducting performance gap analysis…At a minimum the State DOT's process shall address the following in the gap analysis…The gaps, if any, in the performance of the NHS that affect NHS pavements and bridges regardless of their physical condition."[2]

"A State shall establish a process for developing a risk management plan. This process shall, at a minimum, produce the following information…Identification of risks that can affect condition of NHS pavements and bridges and the performance of the NHS, including risks associated with current and future environmental conditions, such as extreme weather events, climate change, seismic activity, and risks related to recurring damage and costs as identified through the evaluation of facilities repeatedly damaged by emergency events carried out under part 667 of this title. Examples of other risk categories include financial risks such as budget uncertainty; operational risks such as asset failure, and strategic risks such as environmental compliance."[3]

"An asset management plan shall discuss how the plan's investment strategies collectively would make or support progress toward…Improving or preserving the condition of the assets and the performance of the NHS relating to physical assets."[4]

The following definitions come from 23 CFR 515.5:

"Investment strategy means a set of strategies that result from evaluating various levels of funding to achieve State DOT targets for asset condition and system performance effectiveness at a minimum practicable cost while managing risks."

"Lifecycle cost means the cost of managing an asset class or asset sub-group for its whole life, from initial construction to its replacement."

"Performance of the NHS refers to the effectiveness of the NHS in providing for the safe and efficient movement of people and goods where that performance can be affected by physical assets. This term does not include the performance measures established for performance of the Interstate System and performance of the NHS (excluding the Interstate System) under 23 U.S.C. 150(c)(3)(ii)(A)(IV)–(V)."

"Performance gap means the gaps between the current asset condition and State DOT targets for asset condition, and the gaps in system performance effectiveness that are best addressed by improving the physical assets."

"Risk management means the processes and framework for managing potential risks, including identifying, analyzing, evaluating, and addressing the risks to assets and system performance."

Background Relevant to Fictional State Department of Transportation

Although these chapters are for a fictional State DOT, the data cited are taken from actual State DOTs and anonymized. These examples represent ones found in 2019 TAMPs. They are enhanced to illustrate how State DOTs could more explicitly indicate how their asset management bridge and pavement conditions influence safety, resilience, reliability, freight movement, and other areas of transportation system performance.

Background information about this fictional State is included below to provide context for this fictional agency. State ABC is:

- Including all State-owned pavements and bridges in its TAMP and not only NHS pavements and bridges
- Facing as an east coast agency long-term sea level rise and increasing extreme weather events
- Experiencing climate impacts and recognizing resilience risks, such as lacking a culvert inventory and having an inordinate number of scour-critical bridges
- Contending with NHS bridge conditions that are much worse than national averages, although pavement conditions are good compared to national averages
- Experiencing increasing pedestrian fatalities, which led it to adopt policies to reduce pedestrian crashes
- Prioritizing freight mobility because as an industrialized state its economy is highly dependent on freight movement

- Facing constrained finances and is not able to fully fund all the bridge and pavement investments it would like and must make financial tradeoffs between bridge and pavement programs

The following three fictional TAMP chapters include the Performance Gap Analysis, Risk Management Analysis, and Investment Strategies. Although these three chapters do not include the objectives, measures, and targets TAMP sections, in this fictional scenario, the agency has decided it must accept slightly lower pavement conditions to increase funding to improve its bridge inventory. Therefore, the performance gap analysis section and the investment strategy sections assume the agency already has lowered pavement targets and raised bridge condition targets.

APPENDIX B. PERFORMANCE GAP ANALYSIS PROCESS

Our agency's performance gap analysis section examines gaps between our agency's projected bridge and pavement conditions and our targets. It also examines how condition and data gaps could affect performance in multiple areas such as safety, freight movement, and resilience.

Our DOT established a process for conducting the performance gap analysis so that the gap analysis would lay the groundwork for later sections such as the risk analysis and investment strategies. The process involved the following steps:

1. Tasking our multidisciplinary TAMP Development Team to identify not only condition gaps, but gaps in the performance of the NHS that affect NHS pavements and bridges regardless of their physical condition. Gaps in the performance of the NHS are determined by examining our performance-based plans, programs, and other performance efforts, such as, but not limited to, the SHSP,[1] the State Freight Plan (SFP), the Freight Reliability Index,[2] the CMAQ Traffic Congestion Measures,[3] and the NHS Travel Time Reliability measures.[4]
2. Tasking the TAMP Development Team to review our LRSTP and the MTPs adopted by our metropolitan planning organizations (MPO) to identify planning objectives that could be supported by our TAMP's investment strategies.
3. Coordinating our gap analysis efforts with the target-setting, LCP, and investment strategy efforts
4. Comparing our current conditions to the current bridge and pavement targets
5. Generating from our bridge and pavement management systems forecasts of the bridge and pavement conditions for each of the next 10 years based upon the final preferred investment strategy
6. Comparing the difference, if any, between the forecasted conditions and our agency's condition targets for each of the TAMP's 10 years. That includes comparing any gaps to our Federally required 2-year and 4-year bridge and pavement targets.[5] Federal regulation requires that our TAMP's investment strategies discuss how they achieve an SOGR.[6] We adopted as our definition of SOGR the targeted conditions set for the 10th TAMP year.
7. Linking the Performance Gap Analysis process to the investment strategy efforts to evaluate alternative strategies to close or address the identified gaps before the final gaps were documented
8. Documenting the projected condition gaps after alternative strategies were evaluated and a final preferred investment strategy was selected
9. Documenting how gaps in bridge and pavement conditions could affect performance in other areas, such as safety, freight movement, and resilience
10. Writing the final performance gap analysis section

This coordination between the gap analysis, target setting, LCP, and investment analysis ensures that the performance gap process results in meaningful conclusions. In reviewing gaps and alternative investment strategy options, our agency reluctantly lowered pavement condition targets to accommodate the need for increased bridge investment. As discussed later, we would have preferred to sustain our current pavement conditions. Limited funds, however, led to a tradeoff to lower pavement targets to reallocate funds to improve bridge conditions.

Our gap analysis also identified two categories of gaps that increase risk and could impede our LCP. One category is the significant number of scour-critical bridges. The other is our lack of a culvert inventory. Both put us at risk of extreme weather events and reduce the resilience of our highway network. Bridges and roadways could fail prematurely during extreme weather events if bridges are scour prone or culverts are in poor condition. Such early failures shorten the lifecycle of assets and close roadways during emergencies. Our gap analysis considers how those two categories of gaps could impede our LCP and lower our transportation system's resilience during extreme weather events.[7]

The Current and Forecasted Gaps

Table 1 shows the current conditions, while Table 2 shows the forecasted conditions, targets, and in some cases gaps. Each State establishes its own SOGR.[8] Our agency defined the SOGR as our 10-year targets. For the TAMP, our agency adopted targets based upon the Federal bridge and pavement performance measures, which are the percent good and poor for Interstate pavements, non-Interstate NHS pavements, and NHS bridges.[9] Our agency uses additional targets for selecting projects.

Table 1. Conditions as of 2022.

2022's Current Conditions	Good %	Poor %
Interstate Pavement	53.2	0.4
Non-Interstate NHS Pavement	36	9
NHS Bridges	27	10.1

In Table 2, targets are in rows A and B. Forecasted conditions are in rows C and D. Gaps, if any, are in rows E and F. Positive values in rows E and F reflect conditions that are better than targets. Negative values indicate conditions are forecast to be worse than the targets.

Table 2 shows that targets for good pavement decline gradually over 10 years. That is because investment levels are not forecast to be adequate to sustain the Interstate and non-Interstate NHS pavements in their current condition. The declining targets were set because of the gap analysis process being coordinated with the target-setting, lifecycle, and investment strategy analysis. After evaluating several investment strategies and target levels, the Department determined that a gradual decrease in the amount of good Interstate pavement and increase in poor pavement was unavoidable if sufficient funds were to be allocated to achieve the bridge condition targets.

Table 2. National Highway System (NHS) conditions, forecasts, and gaps.

		Interstate Pavement			Non-Interstate NHS Pavement			NHS Bridges		
		Targets %			Targets %			Targets %		
Rows		2-Year	4-Year	10-Year	2-Year	4-Year	10-Year	2-Year	4-Year	10-Year
A	Good	54	53	51	36	34	32	30	32	35
B	Poor	2	2	2	10	11	14	9.9	8.5	5
		Forecasts %			Forecasts %			Forecasts %		
C	Good	53	52	50	36	35	33	28	30	35
D	Poor	0.4	0.6	1.5	9	10	12	9	8	5
		Gaps %			Gaps %			Gaps %		
E	Good	-1	-1	-1	0	1	1	-2	-2	0
F	Poor	1.6	1.4	0.5	1	1	2	0.9	0.5	0

As seen in Table 2, 2-year, 4-year, and 10-year Interstate forecasted pavement conditions for poor pavements are better than the targets. They are also much better than the 5-percent poor Interstate pavement set as a national maximum allowable level.[10] However, the NHS bridge conditions at the 2-year mark are only 0.1 percent below the 10-percent allowable maximum for poor condition bridges.[11]

The lower pavement targets reflect the investment tradeoff necessitated to reluctantly allow pavement conditions to decline to improve the poor bridge conditions. As can be seen by comparing current Interstate pavement conditions to the targets in row B, the target for percent poor was set lower than current conditions. Also, as seen in row E, the percentage of good Interstate pavements is slightly below target. The lack of gaps in poor Interstate and non-Interstate NHS pavements is the result of lowering targets. Although gaps are minimized, the pavement network changes reflect a slight overall decline. The amount of good pavement slightly declines, and the amount of poor pavement slightly increases.

In contrast, NHS bridge conditions improve, and the gaps decrease between forecasted conditions and targets. As seen in Table 3, the current percentage poor NHS bridge area was 10.1 percent. Not only was that worse than the 10-percent poor allowable maximum, but it was also one of the worst overall condition levels nationally. The historically poor NHS bridge conditions led to the increased bridge investments and the tradeoff to allow pavement conditions to slightly decline.

In addition to Interstate pavements, non-Interstate NHS pavements, and NHS bridges, the TAMP also includes all other State-owned pavements and bridges. The forecasted conditions, targets, and gaps for the non-NHS pavements and bridges are shown in Table 3. The table shows that the non-NHS pavement condition targets were lowered, and bridge targets and conditions raised.

As with the NHS pavements, the agency forecasts a steady decline in non-NHS pavement conditions over the 10-year period as seen in Table 3. This, again, reflects the tradeoff made to increase bridge investments. The non-NHS pavement gaps are 0 because targets were steadily reduced. At the same time, the non-NHS bridge conditions improve but to a lesser amount than for the NHS bridges.

Table 3. Non-National Highway System (NHS) pavement and bridge targets, conditions.

		Non-NHS Pavement			Non-NHS Bridges		
		Targets %			Targets %		
Rows		2-Year	4-Year	10-Year	2-Year	4-Year	10-Year
A	Good	40	39	37	40	42	44
B	Poor	15	16	18	11	10	8
		Forecasts %			Forecasts %		
C	Good	40	39	37	40	42	44
D	Poor	15	16	18	11	10	8
		Gaps %			Gaps %		
E	Good	0	0	0	0	0	0
F	Poor	0	0	0	0	0	0

In summary, although pavement targets were lowered, the reduced targets reflect the "best available" option given the agency's limited finances and its acute need to improve bridge conditions. The tradeoff allows improvement in bridge conditions while pavements remain close to the national condition averages.

Although the agency lowered its targets and eliminated most gaps between targets and conditions, it would have preferred to sustain its 2022 pavement conditions. Figure 23 illustrates the annual financial gap between the inflation-adjusted pavement allocation and the inflation-adjusted investment needed if 2022 conditions were sustained. The financial gap is the difference between the inflation-adjusted need and the inflation-adjusted budget. The investment gap begins at $15.5 million and rises to $248.2 million by 2032. The 2022 need to maintain pavements in current condition is $245 million compared to the budget of $229.5. Then, a 3.5-percent inflation rate is applied. The fixed budget is reduced each year by the inflation rate as shown in the Inflation-Adjusted Budget line. By 2032, the purchasing power in current dollars for the $230 million pavement allocation is $160.71 million.

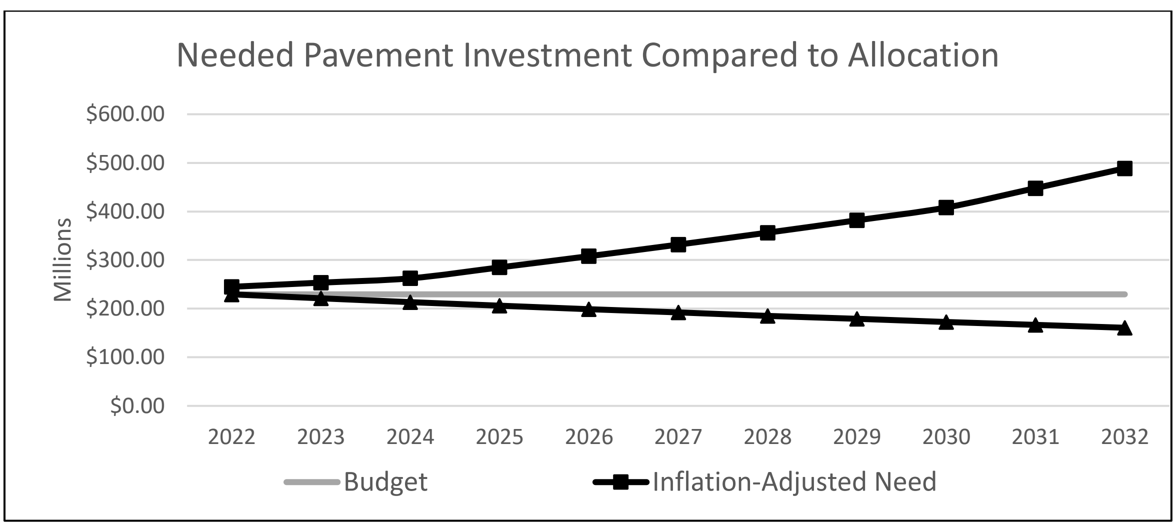


Figure 23. Graph. The financial gap between the inflation-adjusted pavement budgets and the amount needed to sustain 2022 conditions through 2031.

The financial need to sustain current conditions is increased by the inflation rate plus the cost to offset the accumulating backlog of poor pavements and the declining number of good pavements. The agency includes this financial gap information to indicate that if revenues exceed forecasts, increases in the pavement budget would be a highly ranked priority for those additional funds.

Figure 24 and Figure 25 show the gap between the desired percentage of good and poor Interstate pavement and the percentage that will be achieved with the new, lower targets. Although the Interstate conditions will remain well above national minimum conditions, they will be slightly lower than what highway users experience today. In Figure 24 and Figure 25, the lines with squares show forecasted conditions. The solid black lines show the desired condition levels, which are better than the targets our agency had to accept.

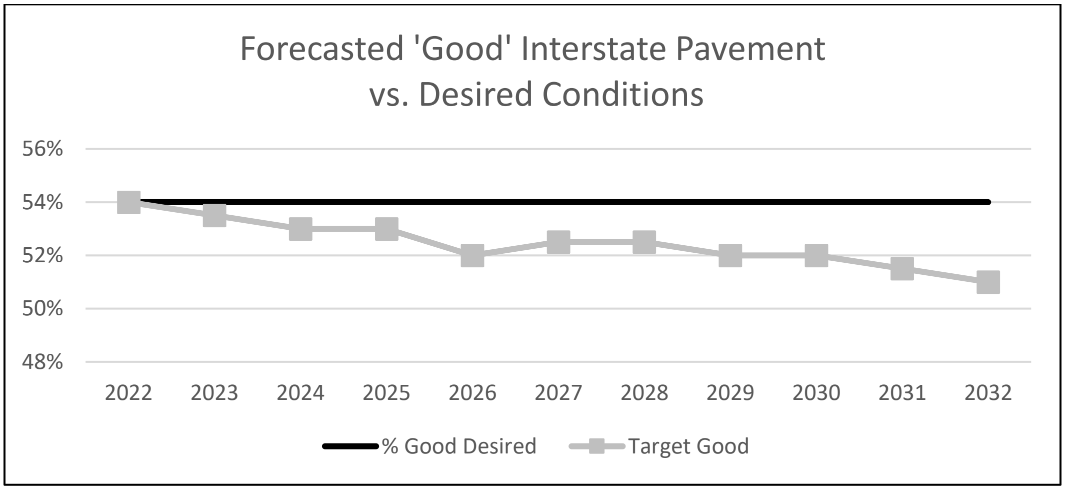


Figure 24. Graph. Forecasted compared to desired good Interstate pavement conditions.

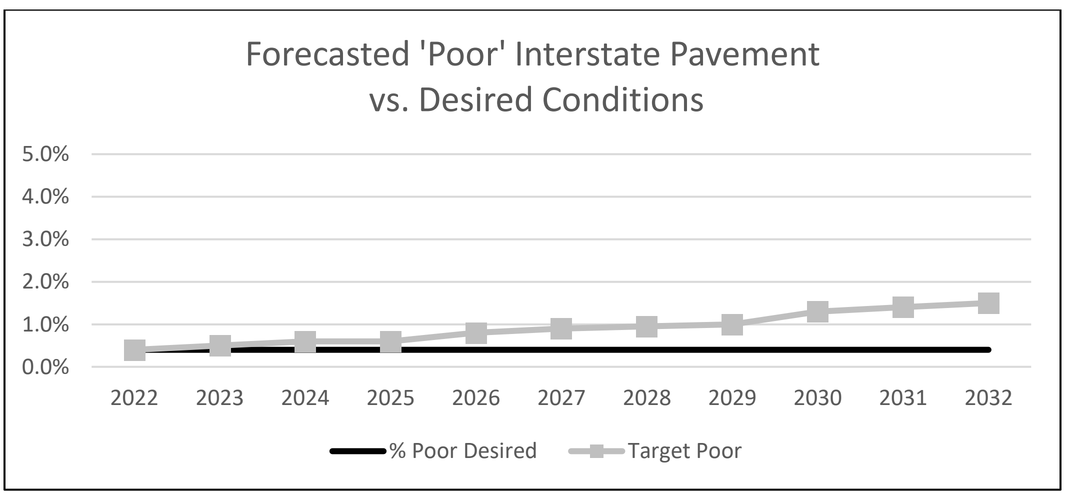


Figure 25. Graph. Forecasted compared to desired poor Interstate pavement conditions.

In contrast to the slight reduction tolerated for pavement conditions, the increased investment in bridges will improve bridge conditions and prevent an even larger investment backlog that was forecast to occur between 2022 and 2032. Figure 26 shows in the solid line what was the previously anticipated bridge budget. It was to start in 2022 at $240 million and rise by 2 percent per year to $293 million by 2032. However, that level of investment would have created an annual investment backlog. That backlog ranged annually from $129 million annually to $208 million. The variation in needed investment reflects the need to pay for specific major bridges as their plans were completed. Such under-investment would have led to decreased bridge conditions and an ever-growing investment backlog. The updated TAMP budget will achieve the condition targets, eliminate the backlog, and allow our agency to sustain the improved conditions beyond the 10 years of the TAMP.

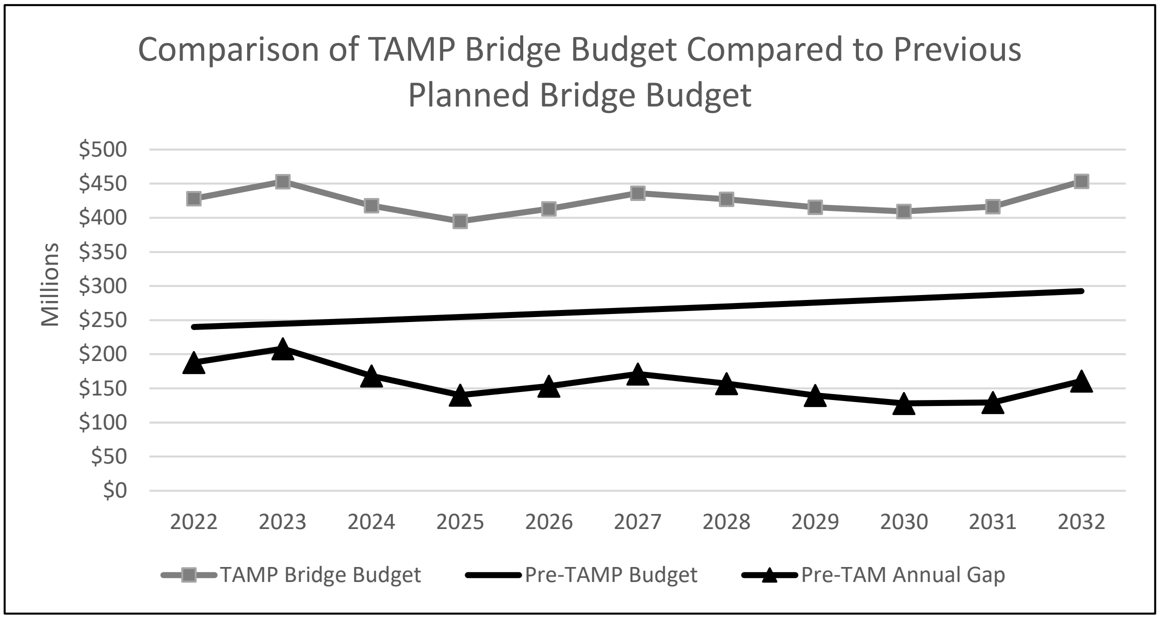


Figure 26. Graph. Comparison of the pre-TAMP bridge budget, the new TAMP bridge budget, and the investment gap closed by the TAMP bridge budget.

The 2023–2032 bridge investment strategies substantially increase bridge investment and are anticipated by 2032 to achieve the NHS bridge condition target of no more than 5 percent of the NHS bridges in poor condition as measured by bridge area. Figure 27 illustrates the steady improvement in the percentage of NHS bridge area in good condition forecast by these investment strategies. Figure 28 shows the steady decrease in the amount of NHS bridge area in poor condition forecasted to occur because of these investment strategies.

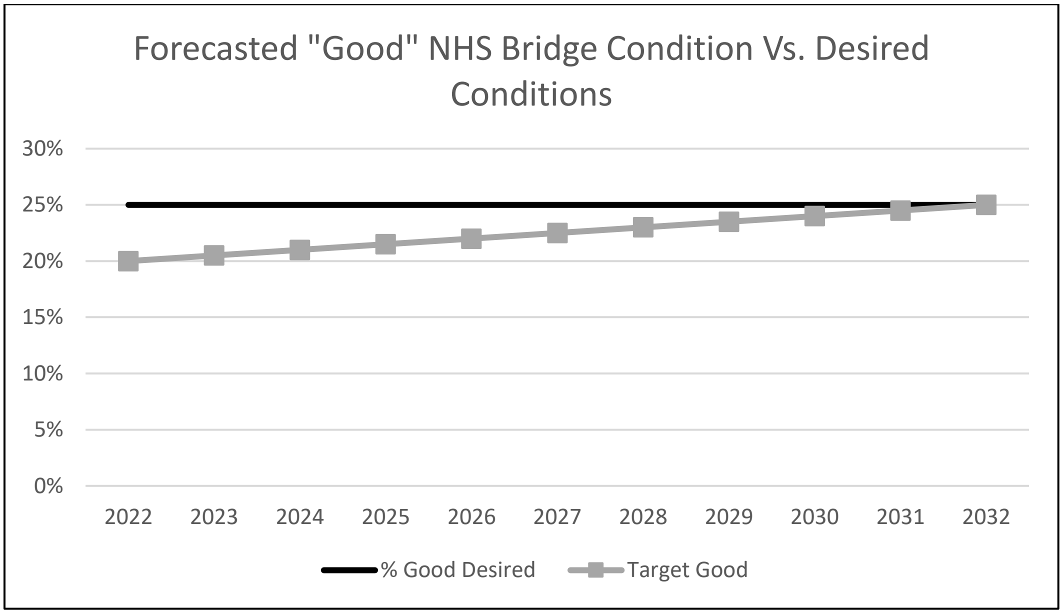


Figure 27. Graph. This chart shows how the percentage of good National Highway System (NHS) bridge area is forecast to steadily increase under the new investment strategy.

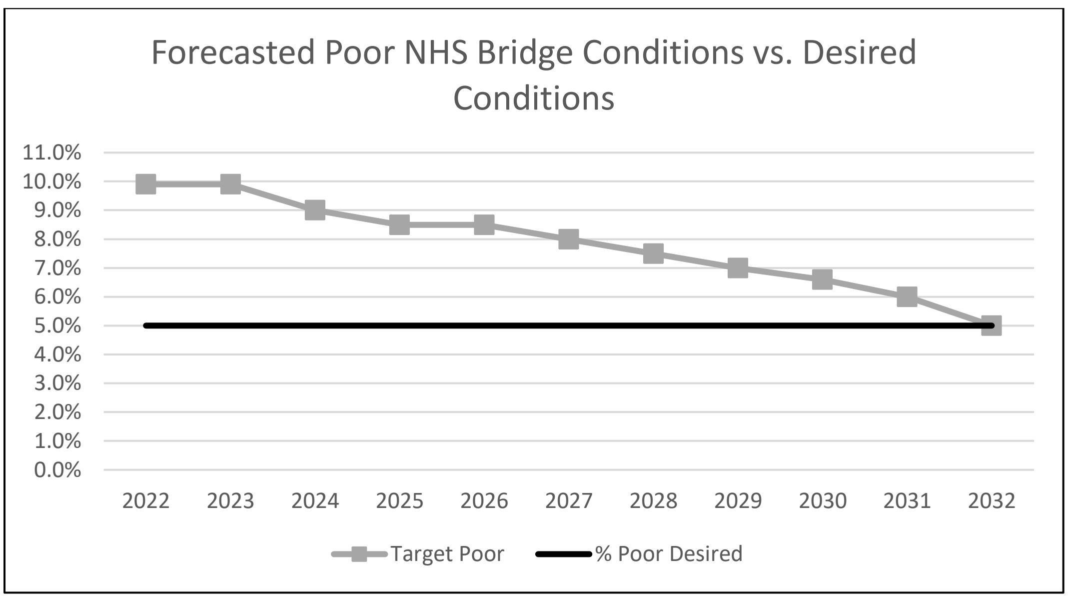
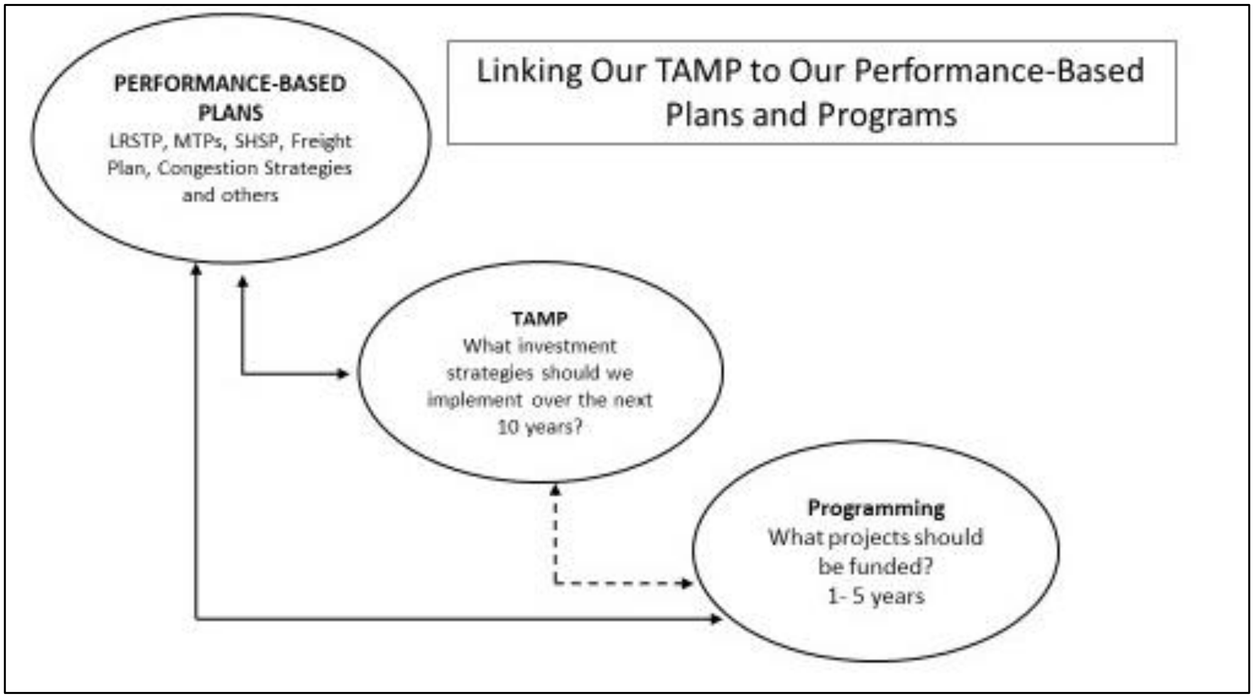


Figure 28. Graph. This graph shows how the percentage of poor National Highway System (NHS) bridge area is forecasted to decline under the new investment strategy.

Identifying Condition Gaps Affecting Performance-Based Plans

Table 2 summarized the gaps between the forecasted bridge and pavement conditions and the bridge and pavement targets that relate to the Federal performance measures. Those measures are set in Federal regulation.[12] In addition to analyzing those condition gaps, the agency also analyzed if any condition gaps affect performance in other areas such as safety, freight movement, and resilience or extreme weather as seen in Figure 29. The TAMP is influenced by, and influences, other transportation plans and performance programs.



LRSTP = long-range statewide transportation plan; MTP = metropolitan transportation plan; SHSP = Strategic Highway Safety Plan.

Figure 29. Graph. The Transportation Asset Management Plan (TAMP) in the planning, programming, and performance process.

To identify condition gaps that could influence our transportation system performance, we took two steps. First, the subject matter experts who developed the TAMP reviewed all our performance-based plans and programs. These include the:

- Statewide Long-Range Transportation Plan
- The MTPs
- The SHSP:
    - Highway Safety Improve Program projects and activities deriving from the SHSP
- The State Freight Plan

- The metropolitan Congestion Management Processes and CMAQ Traffic Congestion Strategies
- The Truck Travel Time Reliability strategies
- The State Resilience Plan

We also invited stakeholders from those plans and programs to workshops to help us identify gaps in bridge and pavement conditions that could influence their performance plans. We looked for opportunities to link our TAMP to the performance-based planning and programming process as shown in Figure 29.

Pavement Conditions and Safety

When viewed narrowly, no safety performance gaps were found that were attributable to the gaps in pavement conditions. For example, asphalt pavement conditions are assessed by a pavement's condition as measured by the IRI, cracking, and rutting. Concrete pavements are measured by IRI, cracking, and faulting. Our agency's SHSP identified no link between elevated crash rates and IRI, rutting, cracking, or faulting. Such a correlation may exist, but it does not appear in our highway crash analyses. Rutting is managed, in part, because it can contribute to crashes. Ruts can retain water that reduce friction, contribute to hydroplaning, and can be a crash factor. However, our SHSP analysis process has not identified rutting as a safety emphasis area.

When viewed more broadly, our agency has identified correlations between some pavement conditions and crash rates. Those conditions related to pavement friction and shoulder adequacy. Although friction and shoulder deficiencies are not captured in the national pavement performance measures, our agency analyzes them to determine if they contribute to higher crash rates. The agency's friction management process assesses high-risk locations annually. These assessments occur at horizontal curves, intersections, areas of high pedestrian traffic, and any location identified as a high-crash area.

The pavement inventory includes data on shoulder width. When roadway departure crashes are analyzed, the width and condition of shoulders are examined to determine if they may be a contributing factor.

Based upon the correlation found between shoulder conditions, friction, and crashes, the agency determined that a pavement performance gap exists between those condition elements and the desired pavement performance. At some locations in the State, either higher friction values or improved shoulder conditions were determined to be a needed safety counter measure. The pavement program will give treatment priority to these sites requiring enhanced shoulders, improved friction, or other pavement-related safety measures. Applying this priority could result in fewer funds available for sustaining pavement conditions as measured by IRI, rutting, faulting, or cracking. However, we prioritize safety even if it could, in the short term, reduce funding to sustain the pavement condition targets. If the safety program requires additional pavement funding, the pavement program will evaluate if pavement condition targets need to be lowered yet again to achieve the safety targets.

Therefore, the pavement program will coordinate with the safety program to measure and address, if warranted, pavement friction at sites including:

- Areas of high pedestrian traffic such as NHS and State routes in residential neighborhoods or areas with high pedestrian traffic
- Mid-block crosswalks and school crossing zones
- Signalized intersections with elevated crash rates
- Safe Routes to School sites
- Horizontal curves, particularly if identified by the HRRRs Program

Shoulders will be improved if they are determined to be a contributing crash factor particularly to rural crashes.

Through the cross-functional TAMP Development Team, the agency's safety program and the pavement program will regularly coordinate analysis of crash data and seek correlations to pavement conditions. To the extent practical, both programs will coordinate on countermeasures where pavement friction or improved shoulders could be crash reduction factors (CRF).

Bridge Conditions and Freight Mobility

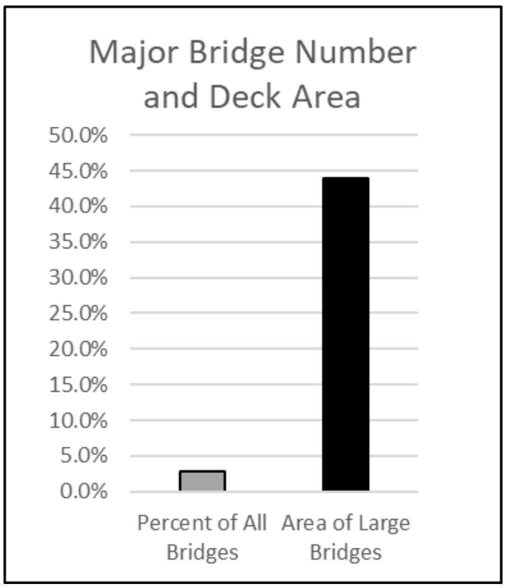


Figure 30. Graph. The major bridges are only 2.9 percent of all National Highway System (NHS) bridge area, although they comprise 44.1 percent of all NHS bridge deck area.

Another area where asset condition and transportation system performance overlap relates to the State's bridges and future freight volumes. Presently, 104 bridges have load limits of which 29 are on the NHS. Those limits occasionally lead to longer routes for "super loads," which are prohibited on those structures. The TAMP investment strategies lead to improvement in our bridges and supports the goal of the State Freight Plan for the NHS routes to accommodate permitted super loads which generally are non-divisible loads greater than 80,000 pounds.

Another area of long-term concern includes the subset of Major Bridges. These are bridges that the agency defines as structures that are more than five times larger than the average State bridge. Out of the inventory of 759 NHS structures, 22 are Major Bridges and have more than 9,000 square meters of deck area. Although they are only 2.9 percent of the number of NHS structures, they are 44.1 percent of all the NHS bridge deck area (Figure 30). They are in slightly worse condition than NHS bridges statewide. Of the 22, 4 are already poor and 10 are rated 5, or "low-fair" in the 0–9 bridge rating scale. If these bridges deteriorate to poor condition, they may be load-limited which could lead to long detours for Super Loads. Those load limits would frustrate one of our State Freight Plan objectives.

The bridge staff and the state freight planning staff will incorporate in the next TAMP and State Freight Plan a long-term strategy for ensuring that the State's NHS bridges remain in good repair and capable of handling future super load demands. The bridge staff will develop a 20-year strategy to ensure that the number of load-limited structures does not impede freight mobility, and that plans are in place to keep the Major Bridges at least in fair condition and able to accommodate super loads. We rate bridges as fair if they are in condition state 5 or 6 based upon the National Bridge Inspection Standards (NBIS). The NBIS rates bridges on a 0–9 scale. Those rated 7–9 are good, 5–6 are fair, and 4 or below are poor.

The bridge staff and freight planning staff will coordinate on how to invest the more than $1 billion in Major Bridge funds that are described below in the Investment Strategies section. Our agency substantially increased funding to rehabilitate, reconstruct, or replace the Major Bridges that are in poor condition or could become poor in the next decade. Part of those funds also will be invested in maintenance and preservation to keep the Major Bridges that are in good or fair condition from deteriorating.

Investments in the Major Bridges could also assist with our performance for the Freight Reliability Index, also known as the Truck Travel Time Reliability Index. Three of the Major Bridges are on our one Interstate corridor that is included on the FHWA's list of the top 100 Freight Bottlenecks.[13] As our bridge staff and freight staff coordinate on improvements to these bridges, the structures' need for improved ramps or additional lanes will be considered to support our Freight Reliability performance.

Preparing for Future Demand

Our agency predicts that truck freight volumes will increase annually by between 1.5 and 2 percent. That growing demand will increase the impact caused by trucks on our bridges, pavements, and upon our traffic congestion. Trucks create impacts disproportionate to their numbers. For example, the Highway Capacity Manual estimates that on urban freeways, large trucks create the equivalent congestion of between 2 and 4 automobiles. On two-lane roads with rolling terrain, the impact is even greater. Our pavement and bridge management systems condition forecasts in Figure 24 through Figure 28 anticipate this truck growth. The growth in truck freight was another factor in influencing our forecasts of future bridge investment needs.

The rate at which truck volumes increase remains an uncertainty that could affect our assumptions about pavement and bridge conditions, as well as traffic congestion. If truck volumes increase considerably, particularly in areas of rolling terrain or near congested interchanges, our assumptions about investment needs and congestion levels may have to be updated.

Asset Conditions and Resilience

The TAMP Development Team in reviewing agency strategic objectives and asset conditions identified three areas of concern where asset conditions may affect the transportation system's resiliency. Those three areas are:

- Pavement sections subject to storm surge and sea-level rise

- Scour-critical bridges
- Culverts lacking accurate inventory and condition data

Our DOT conducted an FHWA-sponsored resilience pilot study that identified no roadway sections threatened by sea level inundation within the 10 years of the TAMP. If sea levels rise as predicted, within 50 years, then up to 25 miles of coastal roadways will face frequent inundation. However, already, slightly more than 12 miles of coastal roadways are threatened by storm surges during hurricanes. Those represent a gap in two areas. First, their closure temporarily impedes evacuation and emergency assistance. Second, pavements in those sections may prematurely deteriorate from inundation. Research repeatedly has shown that saturated pavement bases can lead to accelerated deterioration.[14,15]

To address these gaps, the pavement staff will consider additional mitigation to those storm-surge-prone sections when they are next scheduled for treatment. Additional treatments could include enhanced drainage structures, elevation of the lowest sections, and enhanced pavement designs to compensate for the saturated roadway bases.

The TAMP Development Team also identified 40 NHS structures with a scour rating of 3. That rating is defined as scour critical with foundations unstable for calculated scour conditions.[16] To address this long-term performance gap, the bridge staff will factor the scour critical rating of structures into the project-selection criteria. The bridge program funding has increased, and the additional resources are expected to not only improve overall conditions but also reduce the number of scour-critical structures.

The final gap related to asset conditions and resilience is with the State's incomplete culvert inventory. The current gap relates to information. Without complete inventory and inspection data, the agency is not able to determine whether culverts present a resilience gap to pavements and to mobility during storm emergencies. If culverts are in poor condition, they could be at risk of failing during storm events. They can also impede good drainage that could accelerate pavement deterioration. Also, the agency would like to include culverts in the next TAMP but cannot do so without knowing their number, age, condition, and size. As part of the TAMP's bridge investment strategy, funds are included to complete and maintain an inventory of all State-managed culverts. For the next TAMP, the degree to which culverts present a resilience threat can be determined.

Performance Gap Analysis Summary

The investment strategies that will be discussed in a later section will reduce the agency's current bridge condition gaps. The percentage of poor condition NHS bridges will be reduced by approximately 50 percent. Closing that gap represents a major improvement in bridge conditions. It also allows the DOT to achieve its target of no more than 5 percent poor for NHS bridge conditions by deck area. This will be better than the maximum amount of 10 percent poor set in Federal regulation.[17]

However, the cost of those long-delayed bridge investments requires tradeoffs. As a result, the agency has set lower pavement targets. Although few pavement condition gaps are shown in this section, that is because the agency has lowered the targets to realistically reflect what can be achieved with available resources. These new lower targets tell the public what pavement conditions they can expect, and they give the agency a benchmark to achieve. Although the pavement conditions and targets have been lowered, the conditions are still near national averages and better than the Federal allowable minimum conditions.[18]

Although the agency is forecasting to meet the official pavement targets, this TAMP emphasizes that if funds allowed, the DOT would retain the higher current conditions as the 10-year target. If resources exceed the revenue forecasts, investing more to achieve higher pavement conditions will be a priority consideration. Our TAMP is one means by which we are communicating to legislators and the public that they will experience slightly declining pavement conditions without additional revenues. We want the TAMP to be a realistic document that accurately communicates the realities facing our State's transportation network.

APPENDIX C. MANAGING RISKS TO TAMP OBJECTIVES

Risk Chapter Background

The FHWA report "How Pavement and Bridge Conditions Affect Transportation System Performance" illustrates how assets in good condition can support progress toward multiple transportation objectives. This document presents a risk chapter as if it were developed by a fictional State DOT that identifies condition risks that could affect performance. This example is intended to convey how this fictional DOT managed risks to its TAMP objectives. This chapter includes two major elements. First, it identifies, assesses, and describes the agency's response to the risks facing its asset management objectives. Second, it illustrates how an agency could use FHWA risk guidance to manage its asset management risks.

Risk Management Analysis

As noted in the FHWA definition, risk is more than only threats. Risk means the positive or negative effects of uncertainty or variability upon agency objectives.[1] Our TAMP uses "threats" to indicate the negative effect of uncertainty or variability and "opportunity" to refer to their potentially positive effects.

Although threats, such as sea level rise and extreme weather, are risks, so are other uncertainties that could affect our agency's asset management objectives. A few examples include higher-than-expected construction cost inflation that prohibits us from affording all the needed bridge and pavement projects, or a risk could be inaccurate forecasts from our bridge and pavement management systems. An inaccurate forecast could cause the agency to overestimate or underestimate the funds needed to sustain assets in good condition. A third example could be an unexpected increase in the rate of deterioration in some of the older bridges and pavement sections. That could cause us to reallocate resources to arrest unexpected condition declines. Some risks could be opportunities. Some new materials and processes may be unproven but could lower costs and improve asset performance, or inflation could be less than forecasted. Our agency generally tries to mitigate threats and capitalize on opportunities.

The approach used in our TAMP to manage asset risks is based upon FHWA guidance entitled Incorporating Risk Management into TAMPs.[2] This chapter generally follows the steps suggested in that guidance.

Organizing the Risk Team

The agency formed a diverse risk management team to develop the risk analysis and response strategies. Because risk can come in many forms and directions, the approach we used was to have a diverse team to anticipate the numerous risks that could face the TAMP objectives. Delivering the investment strategies required relying on multiple groups from within and outside of our agency. Some events such as Federal consideration of a new environmental regulation could affect the project-delivery schedule. International steel and oil markets affect costs. A more rapid-than-expected rise in sea levels could accelerate the State's coastal impacts. New innovations in chip seals could provide more low-cost pavement-treatment opportunities. To address these challenges, our agency wanted to gather multiple perspectives.

Among the risk team members were staff from:

Pavement management	Bridge management	Asset management
Information technology	Maintenance	District leadership
Environmental services	Statewide planning	Metropolitan planning
Safety	Estimating	Freight planning
Materials	Risk management	Finance

Reviewing Objectives and Their Context

One of the early steps taken was for a risk-management team facilitator to start the first in a series of risk workshops by reviewing the asset management objectives and the context around them. The risk team members were reminded of the agency's two relevant objectives to:

- Manage the assets with lifecycle strategies to lower costs and improve long-term asset conditions
- Manage the assets so they contribute to safety, mobility, resilience, sustainability, and environmental justice as well as to achieve condition targets and sustain an SOGR

Important context around the risk identification effort included providing an overview of high-level strategic issues facing the agency.

The first strategic issue was poor NHS bridge conditions. Figure 31 shows that, although the percentage of poor NHS bridge area has declined, it still exceeds the DOT's target of no more than 5 percent poor bridge deck area. In addition, the agency has not achieved its target of 25 percent good bridge deck area. Therefore, achieving the bridge condition targets is a major goal, and events that could impede their achievement could be significant risks. As will be elaborated upon, risks that could impede achieving our bridge condition targets include unexpectedly high construction inflation, increased storm events that damage bridges, or failure to deliver the needed bridge-improvement projects.

The second strategic issue related to the NHS bridge conditions is the disproportionately significant impact on the bridge conditions caused by the State's largest structures. Out of the 759 NHS structures, the 22 largest comprise 44.1 percent of all NHS bridges by deck area. Those bridges are only 2.9 percent of the total NHS bridge inventory, but they present a disproportionate risk to the bridge budget, bridge conditions, and resilience. In simple terms, if we do not improve and sustain those Major Bridges, it is mathematically impossible to achieve our statewide bridge condition targets. These Major Bridges are not just disproportionately large, they are disproportionately expensive, disproportionately complex to repair, and have disproportionate impacts on our freight and mobility objectives.

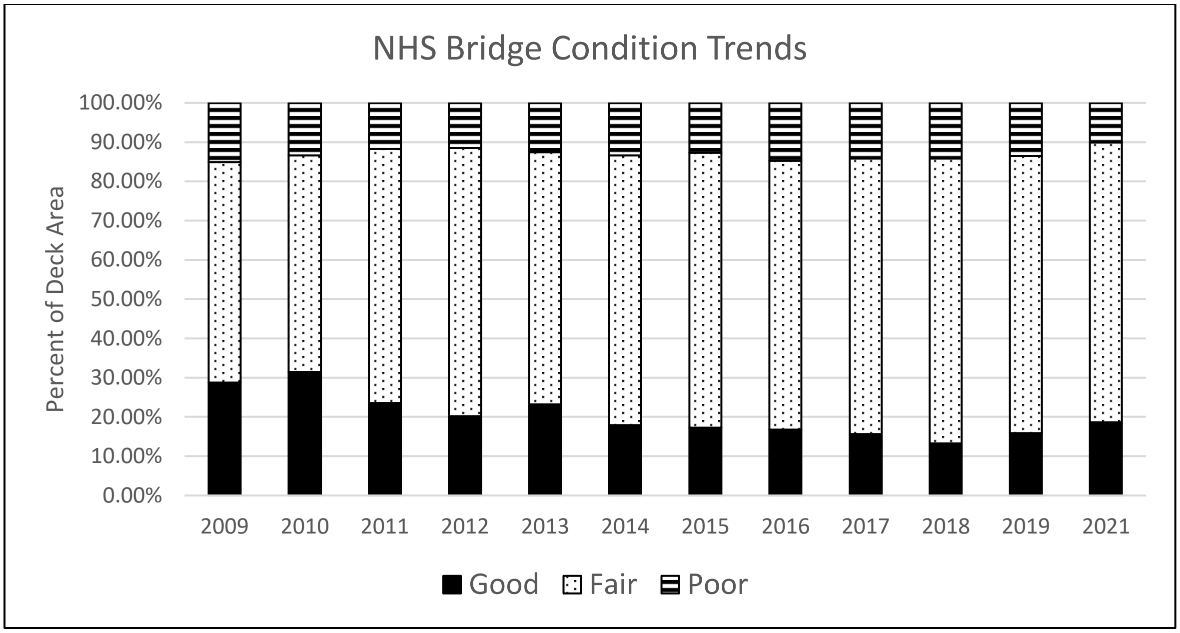


Figure 31. Chart. Trend line of past National Highway System (NHS) bridge conditions.

These Major Bridges are below average compared to statewide bridge conditions. The average NHS bridge condition statewide is 5.82 on the 0-9 NBI rating system. For the 22 Major Bridges, the average NBI condition rating is 5.27. The Major Bridges' condition contributes disproportionately to our overall poor bridge conditions. Four of the 22 are already poor and represent 47 percent of all the poor bridge area on our State highway system.

The Major Bridges also represent a disproportionate resilience risk. Table 4 of the 22 Major Bridges illustrates the number of scour critical structures. They include 5 with a low scour rating of 3 and another 5 with scour ratings of 5. A rating of 3 indicates the bridge is scour critical and determined to be unstable for calculated scour conditions. [3] Even with a low scour rating, a bridge can be rated higher than poor. The "lowest rating" is based only on the condition of the deck, superstructure, and substructure.[4, 5]

A rating of 5 indicates foundations are determined to be stable for assessed or calculated scour condition. However, it is one condition level way from 4 which indicates that action is required to protect exposed foundations. Table 4 illustrates the number of scour critical structures. It also illustrates that only six of the largest bridges have any components rated 7 or above, which is good. Although only four currently are poor, the overall condition of these large bridges could present a long-term risk to the condition targets and budgets.

The third strategic issue is pedestrian and bicycle safety and ensuring that each bridge project includes pedestrian walkways and bike lanes where warranted. Based on the agency's safety objectives, the agency leadership has instructed every unit in the DOT to take steps to reduce the high number of pedestrian and bicycle fatalities. The State's overall highway fatality rate has fallen from 1.24 per 100 million miles travelled in 1994 to 1.02 by 2019. However, the number of pedestrian and bicycle fatalities has not fallen commensurately. The most recent 5-year average number of pedestrian and bicycle fatalities remains about 42 deaths per year, disproportionately high among the young, the elderly, and people in environmental justice communities. One of the strategic initiatives is to combine efforts across the department to lower the pedestrian crash numbers.

Table 4. These are the 22 major bridges and their condition. Components in poor condition or if a structure is scour critical are flagged with black cells.

Structure	Bridge Area	Deck	Super	Sub	Scour Rating	Average Daily Traffic	Condition	Lowest Rating
001	58,902	6	5	5	5	58,206	F	5
002	58,244	6	5	6	5	60,673	F	5
003	56,569	5	5	6	8	24,012	F	5
004	54,991	6	6	5	8	157,934	F	5
005	50,651	6	6	6	3	36,410	F	6
006	43,343	6	6	5	8	129,187	F	5
007	30,337	6	6	5	N	128,795	F	5
008	25,677	7	7	7	8	17,677	G	7
009	21,040	5	5	4	8	19,479	P	4
010	19,814	7	7	7	5	48,000	G	7
011	19,713	6	6	6	8	82,969	F	6
012	19,164	7	7	7	5	184,030	G	7
013	19,044	5	5	6	8	127,595	F	5
014	18,869	6	3	3	3	9,480	P	3
015	16,960	7	6	6	8	42,201	F	6
016	14,363	6	6	6	3	20,816	F	6
017	13,521	6	4	6	3	88,550	P	4
018	12,232	6	5	6	8	61,724	F	5
019	12,196	4	5	5	5	206,049	P	4
020	11,103	7	7	6	3	89,100	F	6
021	9,951	7	6	5	N	53,251	F	5
022	9,225	6	6	5	N	53,251	F	5

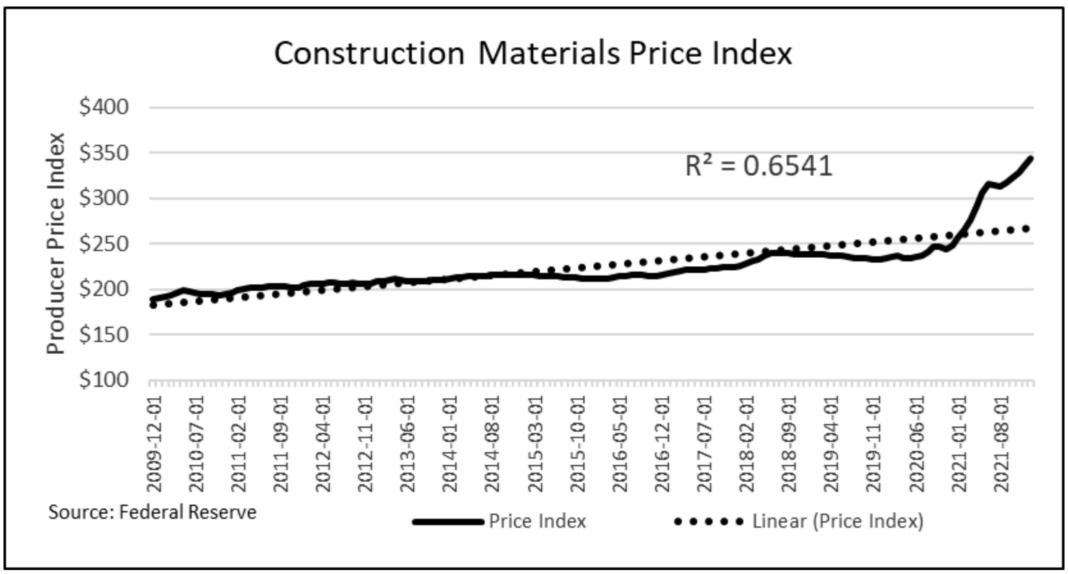
Cells that are highlighted indicate components that are poor or bridges that are scour critical.

A fourth issue important to the DOT's risk context is construction inflation. In the 12 months preceding the TAMP, construction inflation rose at more than twice the expected rate of 3 percent a year. Price hikes were attributed to material and labor shortages and abruptly increasing demand after the pandemic.

Figure 32, Figure 33, and Figure 34 illustrate the price volatility seen in the months leading up to the TAMP update. National prices for steel, diesel, and other construction materials rose sharply in the preceding 12 months.

An uncertainty for the TAMP is whether over its 10-year period, prices will regress to the mean of the long-term average inflation or whether the high prices seen at the time of the TAMP update represent a new plateau of prices.

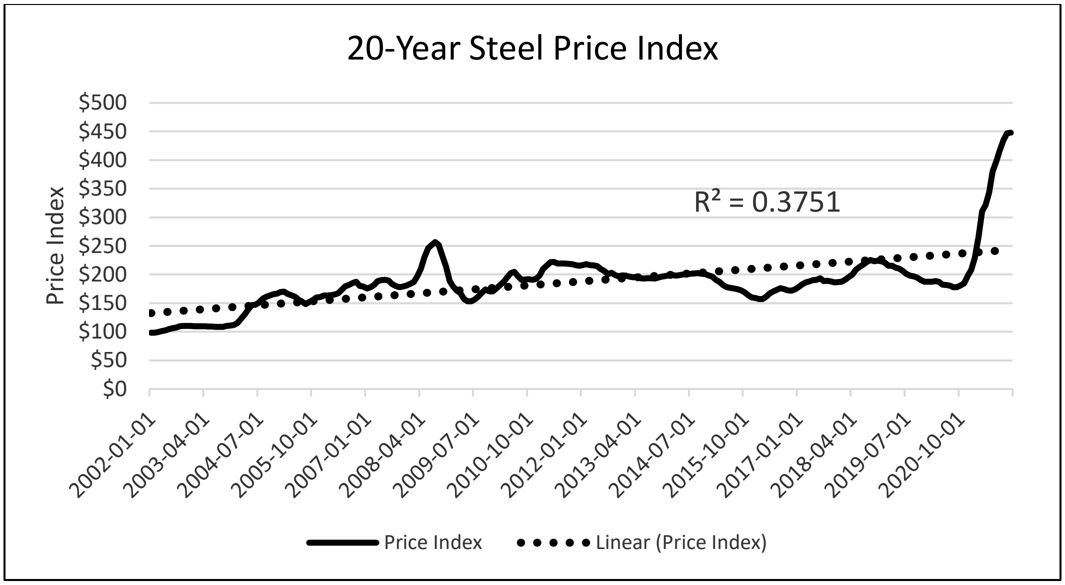
Figure 32, Figure 33, and Figure 34 each show the cost trends and a linear regression line with an R^2 value. The R^2 calculates how closely the straight line resembles changes over time. A perfect correlation between the line and prices would produce an R^2 value of 1.0. The regression line (R^2) for construction materials captured 65.41 percent of the past price volatility. The R2 value of the regression line for steel captures only 37.51 percent of the past price volatility. The R^2 value of 0.1915 for diesel prices indicates that a straight-line forecast would have captured only 19.15 percent of the past price volatility. In other words, the typical straight-line forecast of price increases could underestimate the variability in future prices and represent a risk to our investment strategies.



Source: Federal Reserve.

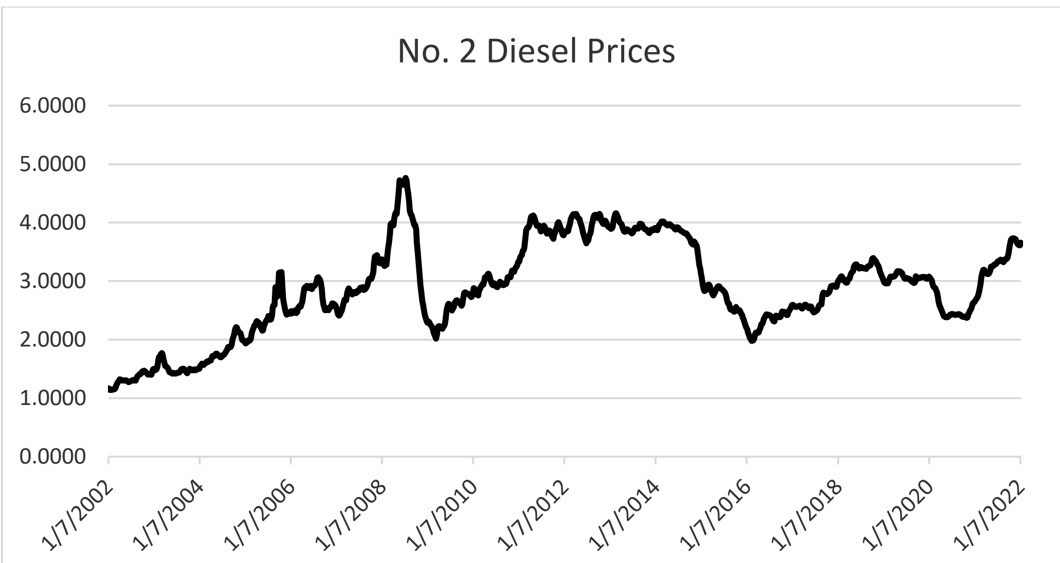
Figure 32. Chart. Change in construction materials price index.

Values in Figure 32 and Figure 33 are in dollars and are depicted as indexes. An index represents a “market basket” of goods that show price changes over time. Figure 32’s construction price index was shown starting in 2009 with a base value of $189.40. Changes in prices can be compared with their change from that base amount in 2009. The steel price index is shown from January 1, 2002, starting from a base index value of $98.30. Changes in prices over time can be compared relative to that base price.



Source Federal Reserve.

Figure 33. Chart. Change in steel producer price index.



Source: U.S. Energy Information Administration.

Figure 34. Chart. Change in diesel prices.

The three charts and the agency's recent bid-price history indicate that substantial uncertainty surrounds the unit costs assumed in the investment strategies. That uncertainty represents what could be a threat to the construction program.

A fifth issue is resilience. Climate change is both a risk and an accelerator of other risks, such as increased flooding, higher temperatures, and greater coastal erosion, which can translate into increased risk to the SOGR to pavements and bridges. Our agency is an active member of the State Resilience Task Force and contributor to the State's Resilience Plan. Our TAMP's response to risks caused by higher sea levels and more extreme weather represents our department's contribution to the State Resilience Plan.

The Risk Identification Process

After reviewing the strategic objectives and the major context issues, a facilitator led the agency's workshop participants through a risk identification process. This involved working in small groups to hear from each participant. Exercises were included to ensure that participants got to express their opinions and to minimize "group think." Group think is when members get steered into an apparent consensus through the advocacy of one or two assertive participants.

The group wrote risk statements with a subject, verb, and object. The detail provided by such statements facilitated the later assessment, prioritization, and response to the risks. The risk register includes the risk statements members produced.

The Risk Assessment Process

After refining their risk statements, members assessed the likelihood and consequence of each risk using the risk matrix in Figure 35. Members expressed their own judgment about the likelihood and consequence of each risk. Negotiation and compromise were sometimes needed for the group to agree on the final likelihood and consequence value for a risk.

Risk Consequence Matrix						
Likelihood		Values	L X I = Consequence			
	Almost Certain	5	5	50	200	350
	Probable	4	4	40	160	280
	Possible	3	3	30	120	210
	Rare	2	2	20	80	140
	Exceptionally Rare	1	1	10	40	70
			Values			
			1	10	40	70
			Low	Moderate	High	Severe
			Impact			

Figure 35. Chart. A likelihood and impact matrix.

The risk matrix is designed to help separate high-impact immediate risks from others, such as high-impact low likelihood ones. The use of numeric impact and likelihood values is intended to help differentiate high risks from low ones. The risk register includes the assessment values that were computed.

The agency's risk assessment process emphasized the identification of opportunities, as well as threats. The nonregulatory AASHTO Guide for Enterprise Risk Management states that risks include uncertainty, variability, threats, and opportunities. The AASHTO Guide states that few opportunities exist without taking some risk. An example of an opportunity is trying new construction materials. However, this opportunity comes with a risk of higher costs or uncertainty about how the materials will perform over time.

In Table 5 and Table 6 are the threats and opportunities the risk management team identified.

Table 5. Threats risk register.

Threats Risk Register					
No.	Event	Impact	Likelihood	Consequence	Value
R1	Rising and unpredictable construction prices…	…create uncertainty about whether pavement and bridge allocations will be adequate to achieve condition targets.	Almost Certain	High	200
R2	Poor-condition, scour-critical bridges…	…remain a hazard to the long-term safety and resilience of the transportation network.	Almost Certain	High	200
R3	Continued poor drainage conditions…	…could lead to repeated water quality violations, increase localized flooding, and damaged pavements.	Almost Certain	High	200
R4	The increase in the size of our construction program without an increase in our State’s construction industry capacity…	…could lead to fewer bidders per project, increased competition for materials, and lead to higher bid prices that reduce the effect of investment strategies.	Possible	High	120
R5	Rising sea levels, storm surges, and hurricane probabilities…	…threaten the resilience of our transportation network, disruption to planned bridge and pavement programs, and an increased rate of bridge and pavement deterioration.	Possible	High	120
R6	Declining pavement conditions could lower skid values and…	…threaten achievement of pavement-condition targets and could impede plans to reduce pedestrian fatalities.	Possible	High	120

Threats Risk Register					
No.	Event	Impact	Likelihood	Consequence	Value
R7	Loss of key staff with unique asset management skills…	… could reduce the department’s ability to manage bridge and pavement management systems and conduct lifecycle planning (LCP).	Probable	Moderate	40
R8	A major seismic event …	… could cause major damage to bridges, pavements, roadways, and other assets.	Exceptionally Rare	Moderate	40
R9	More than 900 lane miles of 40-year-old concrete Interstate pavement …	… could strain the pavement budget, deteriorate rapidly, and cause the department to not meet our pavement-condition targets.	Probable	Moderate	40
R10	Decreasing political support for asset management…	…could lead to legislative redirection of funds and inability to afford the investment strategies.	Possible	Moderate	30
R11	Uncertainty about the deterioration curves in the new bridge management system…	… could lead to under or over-estimation of our bridge investment needs.	Possible	Moderate	30
R12	If our bridge conditions are not improved…	… their continued deterioration could eventually impede our freight reliability.	Possible	Moderate	30
R13	If pavement-preservation treatments are not effectively implemented…	…pavement conditions will decline more than expected and costs to achieve condition targets could exceed the pavement budgets.	Possible	Moderate	30
R14	An incomplete culvert inventory…	…could lead to not identifying failing culverts that could collapse, create hazards, and lead to flooding.	Possible	Moderate	30

Table 6. Opportunities risk register

Opportunities Risk Register					
No.	Event	Impact	Likelihood	Consequence	Value
R15	Coordination between pavement, bridge, and drainage programs…	…could identify economies of scale and shared funding opportunities to improve both asset conditions and drainage performance.	Almost Certain	High	200
R16	Coordination between the pavement and safety programs…	…could identify opportunities for the pavement program to enhance pavement friction, improve crosswalks and other important pedestrian-safety features, and reduce pedestrian fatalities.	Probable	High	160
R17	Coordination between the pavement program and the High-Risk Rural Roads (HRRRs) Program…	…could provide low-cost opportunities to enhance shoulders, friction at curves, and other factors affecting rural crash rates.	Probable	High	160
R18	The bridge program and the freight program could coordinate long-term needs…	…to identify how the planning and sequencing of bridge projects on major freight routes could complement long-term freight mobility.	Possible	High	120

The Threats Risk Register was produced during the workshop. It shows the six highest scoring threats. Those generated a likelihood and impact value above 100. The top six selected will be treated as enterprise threats that could seriously impede the asset management objectives.

Those six are:

R1–Rising and unpredictable construction prices create uncertainty about whether the pavement and bridge allocations will be adequate to achieve condition targets.

R2–Poor-condition, scour-critical bridges remain a hazard to the long-term safety and resilience of the transportation network.

R3–Continued poor drainage conditions could lead to repeated water quality violations, increase localized flooding, and damage pavements.

R4–The increase in the size of our construction program without an increase in our State's construction industry capacity could lead to fewer bidders per project, increased competition for materials, and lead to higher bid prices that reduce the effect of investment strategies.

R5–Rising sea levels, storm surges, and hurricane probabilities threaten the resilience of the transportation network and disruption to planned bridge and pavement programs.

R6–Declining pavement conditions could lower skid values and threaten achievement of pavement-condition targets and could impede plans to reduce pedestrian fatalities.

The workshop also produced four opportunities that were spurred by the agency's objectives and by the strategic initiative to reduce pedestrian crashes. Those opportunities are:

R15–Coordination between pavement, bridge, and drainage programs could identify economies of scale and shared funding opportunities to improve both asset conditions and drainage performance.

R16–Coordination between the pavement and safety programs could identify opportunities for the pavement program to enhance pavement friction, improve crosswalks and other important pedestrian-safety features, and reduce pedestrian fatalities.

R17–Coordination between the pavement program and the HRRRs Program could provide low-cost opportunities to enhance shoulders, friction at curves, and other factors affecting rural crash rates.

R18–The bridge program and the freight program could coordinate long-term needs to identify how the planning and sequencing of bridge projects on major freight routes could complement long-term freight mobility.

The objective to manage assets not only for condition but also to support multiple performance areas led the risk team members to identify opportunities for different programs to cooperate. Those include the R15 opportunity to pool funds to achieve economies of scale between the pavement, bridge, and drainage programs. Risk team members saw the lack of a drainage inventory and deteriorating drainage conditions as a high risk to resilience and to compliance with water quality standards. Workshop participants said poor drainage can accelerate pavement deterioration, exacerbate flooding, delay emergency response, and contribute to crashes. Rather than treating drainage needs as a “silo,” the risk team members saw an opportunity for at least three programs to coordinate to improve drainage.

The Risk Prioritization Process

The next step in the process is risk prioritization. This differs from risk assessment in that this step prioritizes risks based upon an agency’s ability to respond to risks and its risk appetite. Some risks, such as international oil price increases, cannot be prevented by an agency. The risk response may involve monitoring and adjusting to prices but not preventing price increases. In contrast, a risk such as inadequate asset data is within an agency’s control. Mitigating inadequate data could have a high response priority because it is something that an agency can control and manage.

In the risk prioritization process, the agency also considers its “risk appetite.” The risk appetite in this case was a qualitative threshold based upon agency policy. For example, through policy, the agency expressed no tolerance for increases in pedestrian crashes. Therefore, risk mitigation strategies to reduce pedestrian crashes will be a priority. Similarly, the agency’s policy of enhancing resilience led the agency to tolerate less risk for bridge scour. The risks chosen for response strategies were ones that were highly rated and which the risk team believed our agency could influence.

The prioritization led directly to the next step, identifying risk-response strategies.

Identifying Risk Response Strategies

Through another series of workshops, the risk team members identified risk-response strategies (Table 7 and Table 8). The term “risk-response strategies” and not “mitigation” strategies is used to mean strategies to address risks. The response to the risks is not always just to prevent or mitigate them, but to also capitalize upon them. This document uses the term risk-response because some of the risks were threats while some were opportunities.

Risks 1–6 are the top-priority risks and their response strategies will be “owned” by the senior agency leadership. That consists of the executive management team that includes the agency’s deputy directors. The appropriate subject-matter staff will “own” other risks.

Table 7. Threats response strategies.

Response Strategies for Threats		
No.	Threat	Response
R1	Rising and unpredictable construction prices create uncertainty about whether the pavement and bridge allocations will be adequate to achieve condition targets.	• Closely monitor bid prices • Track forecasted price trends reported in national trade publications for key inputs such as steel, cement, and diesel • Prepare contingency plans for delaying projects or reducing scope items • Consider if increased use of chip seals or low-cost pavement products could be substituted for pavement resurfacings • Analyze the long-term impact of delaying some high-cost pavement reconstruction projects
R2	Poor-condition, scour-critical bridges remain a hazard to the long-term safety and resilience of the transportation network.	• Continue close management of the bridge project-development program to ensure that the programmed bridges are delivered as planned • Maintain the stream monitoring and frequent inspection programs to ensure that storm events do not increase scour risk
R3	Continued poor drainage conditions could lead to repeated water quality violations, increase localized flooding, and damage pavements.	• Continue funding and staffing the enhanced drainage maintenance program • Look for opportunities to bundle drainage-improvement projects with bridge and pavement projects
R4	The increase in the size of our construction program without an increase in our State's construction industry capacity could lead to fewer bidders per project, increased competition for materials, and lead to higher bid prices that reduce the effect of investment strategies.	• Publicize the increased size of the expected construction program in hopes of attracting additional competition through new firms forming or existing firms expanding

Response Strategies for Threats		
No.	Threat	Response
R5	Rising sea levels, storm surges, and hurricane probabilities could threaten the resilience of our transportation network, disruption to planned bridge and pavement programs, and an increased rate of bridge and pavement deterioration.	• Complete the vulnerability analysis of roadways and bridges at risk of increased sea levels, storm surges • Incorporate the need to elevate some structures into the lifecycle plans for coastal structures • Develop rapid-response plans to be able to restore service quickly if roadways or bridges are damaged
R6	Declining pavement conditions could lower skid values and threaten achievement of pavement-condition targets and could impede plans to reduce pedestrian fatalities.	• Prioritize skid-measurement and response at pedestrian-heavy locations • Coordinate the pavement program, skid-measurement programs, and pedestrian safety program to ensure opportunities to enhance pedestrian safety are found
R7	Loss of key staff with unique asset management skills could reduce the agency's ability to manage bridge and pavement management systems and conduct lifecycle planning (LCP).	• Conduct transition planning to identify when key staff may retire so that training can avoid abrupt loss of staff expertise • Consider outside contract resources to augment key skills
R8	A major seismic event could cause major damage to the bridges, pavements, roadways, and other assets.	• Continue the gradual seismic retrofit program to enhance the vulnerable structures • Incorporate needed seismic resilience features in new bridge designs • Coordinate with emergency management staff to develop response plans in the event of a major seismic event
R9	More than 900 lane miles of 40-year-old concrete Interstate pavement could strain the pavement budget, deteriorate rapidly, and cause the department to not meet our pavement-condition targets.	• Be diligent about programming, designing, and delivering the multiple projects to replace or rehabilitate those at-risk pavements

Response Strategies for Threats		
No.	Threat	Response
R10	Decreasing political support for asset management could lead to legislative redirection of funds and inability to afford the investment strategies.	• Emphasize to legislators during budget testimony the long-term cost savings and condition improvement attributable to asset management programs • Update the asset management brochure, website, and video to explain the benefits of asset management • Put a dollar figure on the annualized savings from asset management
R11	Uncertainty about the deterioration curves in the agency's new bridge management system could lead to under or over-estimation of bridge investment needs.	• Continue comparing actual observed deterioration rates to update the management system curves • Be prepared to revise bridge-condition forecasts as deterioration curves are enhanced
R12	If our bridge conditions are not improved, their continued deterioration eventually could impede our freight reliability.	• Diligently identify, plan, program, and deliver our bridge program • Apply lifecycle strategies to manage the bridge program to improve conditions for the least cost
R13	If the pavement-preservation treatments are not effectively implemented, pavement conditions will decline more than expected and costs to achieve condition targets could exceed pavement budgets.	• Conduct refresher training for maintenance crews about crack sealing and other preservation activities • Prioritize the delivery of preservation projects • Explore bundling multiple preservation projects to lower costs
R14	An incomplete culvert inventory could lead to the agency not identifying failing culverts that could collapse, create hazards, and lead to flooding.	• Allocate planning funds to complete the culvert inventory • Complete the management system module to monitor and forecast culvert conditions • Ensure culvert inspection and inventory updates are a priority for maintenance garages

Response Strategies for Threats		
No.	Threat	Response
R15	Coordination between pavement, bridge, and drainage programs could identify economies of scale and shared funding opportunities to improve both asset conditions and drainage performance.	• Formally instruct the pavement, bridge, and drainage program staff to coordinate and look for shared opportunities • Conduct a kick-off workshop to spur coordination • In the bridge, pavement, drainage programs, identify the specific projects that will incorporate multiple treatments

Table 8. Opportunities response strategies.

Response Strategies for Opportunities		
No.	Opportunity	Response
R16	Coordination between the pavement and safety programs could identify opportunities for the pavement program to enhance pavement friction, improve crosswalks and other important pedestrian-safety features and reduce pedestrian fatalities.	• Instruct the Highway Safety Improvement Program (HSIP) staff and the pavement staff to develop joint approaches to treat pavements and develop crosswalks to enhance pedestrian safety
R17	Coordination between the pavement program and the High-Risk Rural Roads (HRRRs) Program could provide low-cost opportunities to enhance shoulders, friction at curves, and other factors affecting rural crash rates.	• Instruct the HSIP staff and the pavement staff to develop joint approaches to treat pavements to support the crash-reduction strategies in the rural safety programs

Response Strategies for Opportunities		
No.	Opportunity	Response
R18	The bridge program and the freight program could coordinate long-term needs to identify how the planning and sequencing of bridge projects on major freight routes could complement long-term freight mobility.	• Coordinate the development of bridge lifecycle plans and TAMP investment strategies with the State Freight Plan • Identify the aging, high-volume bridges that are important to bridge conditions, freight mobility, and overall system reliability • Identify opportunities to ensure long-term freight mobility is considered with bridge lifecycle strategies

Integrating Risk Management into Agency Operations

Progress on top priority risk-response strategies will be reviewed quarterly at the standing executive leadership meetings.[6] Each year, the risk team will reconvene. They will:

- Review the agency context and identify major developments that could influence the agency's overall risk profile
- Update the risk register to respond to any economic, political, or policy changes that could influence the department's risks
- Update the risk-response strategies
- Inform the senior agency leadership of high priority risks and potential enterprise risks

Facilities Repeatedly Damaged by Emergency Events

A section of the asset management rule, known as Part 667,[7] requires that TAMPs include a summary of the evaluation of facilities repeatedly damaged by emergency events. The agency's evaluation of sites damaged more than once during emergency events since January 1, 1997, identified 12 such locations. However, more than 150 different locations were damaged at least once during officially declared emergency events since January 1, 1997.

To maintain an accurate list of sites relevant to the Part 667 rule, our agency developed a website of all sites damaged during emergency events since January 1, 1997. The list of sites will be updated after each officially declared emergency event. The updating will allow our agency to identify if any sites beyond the initial 12 are damaged more than once.

When our agency plans to program a project, part of the programming protocol will be to check whether the project is at a location that has been damaged more than once during an emergency. If so, an analysis will be conducted prior to programming to determine how to mitigate, partially, or fully resolve the root cause of the past site failures. The evaluations will consider the risk of recurring damage, the cost of any long-term solution, and the likely success of the solution. The project scope will then include any cost-effective elements intended to avoid damage from future emergency events.

The agency will continue monitoring damage during future emergency events. In addition, pertinent locations that need to be addressed will be considered when developing projects during the statewide and metropolitan planning processes.

APPENDIX D. INVESTMENT STRATEGIES

The FHWA report *How Pavement and Bridge Conditions Affect Transportation System Performance* illustrates how assets in good condition can support progress toward multiple transportation objectives. This is an example TAMP section that illustrates how a fictional agency could link its investment strategies[1] to both achieve asset condition targets, as well as system performance effectiveness.

Introduction to a Fictional Investment Strategy Transportation Asset Management Plan Section

This TAMP section contains our department's investment strategies. These strategies are developed to implement the findings from the other TAMP analyses, such as the lifecycle plan, gap analysis, financial plan, and risk assessment. These investment strategies are intended to meet the department's asset condition targets, support performance of the NHS, and make progress toward the national goals, such as safety, infrastructure condition, congestion reduction, freight movement, system reliability, and environmental sustainability.

The investment strategies for our department are:

- Investment Strategy 1–Invest on average $323 million annually in NHS bridges, excluding Major Bridges, to achieve the department's NHS bridge condition targets by 2032, to support long-term freight mobility, and to enhance resiliency by decreasing the number of scour-critical structures. Major Bridges are defined in the risk analysis chapter as structures that are five times larger than the average agency bridge.
- Investment Strategy 2–Invest approximately $105 million annually in the Major Bridge program. The additional investment in the Major Bridges brings the condition of the Major Bridges equal to the statewide NHS bridge condition and enhances long-term freight mobility.
- Investment Strategy 3–Invest approximately $230 million annually in NHS and non-NHS pavements to achieve the agency's condition targets for the maximum amount of poor Interstate and non-Interstate NHS pavements.
- Investment Strategy 4–Invest approximately 2 percent of the NHS pavement allocation to improve friction, shoulders, or other pavement elements to support the Strategic Highway Safety Program's pavement-related safety emphasis areas.

Closing Condition Gaps

The financial allocations shown in Table 9 are forecast to achieve the department's bridge condition targets, close the department's bridge condition gaps, and achieve a long-term SOGR. As noted in earlier TAMP sections, the department's NHS bridge conditions in 2022 were 10.1 percent poor. The department's target for 2032 is to have no more than 5 percent of NHS bridges rated poor and at least 50 percent of NHS bridges in good condition by 2032.

Table 9 shows an average annual investment of $416 million over the 10-year TAMP period from 2023 to 2032. The year 2022 provides context to compare and contrast the future expenditures to the base year of 2022. The investment strategies substantially increase the bridge allocation to pay for the bridge investments needed to achieve those condition targets. The allocations are based on the lifecycle-based bridge management analysis discussed below and elaborated upon in the Lifecycle Planning section. The allocations for Investment Strategies 1 and 2 are highlighted individually.

The pavement allocations shown in Table 10 are forecast to achieve the pavement condition target of no more than 2 percent of the Interstate pavement in poor condition and no more than 14 percent of the Non-NHS pavements in poor condition, both by 2032. However, as indicated in the Performance Gap Analysis section, the forecasts indicate a 1 percent condition gap may exist for the percent of Interstate pavements in good condition. The department intentionally set a target for good Interstate pavements above the department's forecasted conditions as an "aspirational" target. The department will prioritize increased Interstate pavement investments to close that small gap if additional funding becomes available. The pavement allocations are derived from the lifecycle-based pavement management analysis discussed below and elaborated in the Lifecycle Planning section.

Table 9. Bridge investment strategies allocations with Strategy 1 and Strategy 2 amounts indicated.

Work Types		Bridge Allocation										
		2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Strategy 1	Maintenance	$36	$35	$32	$29	$29	$26	$26	$26	$26	$26	$26
	Preservation	$54	$53	$48	$43	$44	$39	$39	$39	$39	$39	$39
	Rehabilitation	$144	$140	$128	$115	$117	$105	$105	$105	$105	$105	$105
	Reconstruction	$126	$123	$112	$101	$102	$121	$135	$148	$154	$168	$189
Strategy 2	Major Bridge	$68	$102	$98	$107	$121	$145	$122	$97	$85	$78	$94
	Total	$428	$453	$418	$395	$413	$436	$427	$415	$409	$416	$453

The allocations in Table 9 and Table 10 not only achieve most condition targets, but they also contribute to the long-term SOGR that extends beyond the TAMP's decade. The bridge and pavement investment scenarios that were modeled by the management systems sought the best 20-year investment scenarios. The allocations in years 2023 to 2032 represent the first 10 years of those 20-year scenarios. As a result, the investment strategies not only achieve most 2-year, 4-year, and 10-year targets, they are steps along the path to sustaining the SOGR for at least 20 years.

Table 10. The pavement investments strategy allocations.

Work Type	Pavement Allocation										
	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Maintenance	$23	$23	$23	$23	$23	$23	$23	$23	$23	$23	$23
Preservation	$35	$35	$35	$35	$35	$35	$35	$35	$35	$35	$35
Rehabilitation	$92	$92	$92	$92	$92	$92	$92	$92	$92	$92	$92
Reconstruction	$81	$81	$81	$81	$81	$81	$81	$81	$81	$81	$81
Total	$230	$230	$230	$230	$230	$230	$230	$230	$230	$230	$230

Implementing Lifecycle Planning

The bridge and pavement allocations by work types directly support the LCP strategies generated by the bridge and pavement management systems. The lifecycle-based strategies help us to lower lifecycle costs, which are the cost of managing an asset class or asset sub-group for their whole life from initial construction to replacement. Our agency has documented that the lifecycle approach over time improves bridge and pavement conditions and lowers the overall cost of managing assets from their cradle to grave.

The department conducted multiple scenarios with the bridge and pavement management systems analyzing different investment levels and different mixes of treatments. For example, scenarios were modeled with differing dollar amounts for preservation, rehabilitation, and reconstruction. The scenarios produced differing condition levels over a 20-year forecast period. The department selected as the preferred lifecycle plans the bridge and pavement scenarios that resulted in the highest overall network conditions for the available funding. Those two resulted in the fund allocations shown in table 9 and table 10 which are repeated from the Financial Plan.

Implementing Risk Management Strategies

As noted in the Risk Analysis, the department's Major Bridges are in below-average condition and disproportionately impact statewide bridge conditions. To respond to the risk that the conditions of the Major Bridges will further reduce statewide conditions, the department created the Major Bridge funding category. Table 9 indicates the largest investments for those bridges are "front ended" in the first five TAMP years. That allows the department to stabilize the condition of the largest bridges.

The Major Bridge allocation not only implements a lifecycle strategy to sustain network-wide bridge conditions, but it also addresses a high-priority risk shown in the Risk section. Risk R2 states that, "poor-condition, scour-critical bridges remain a hazard to the long-term safety and resilience of the department's transportation network." The Major Bridge program will not only improve the condition of Major Bridges, it also will focus upon those Major Bridges with scour-critical ratings. The intent is to reduce the number of scour-critical Major Bridges, and concurrently extend the life of those structures by rehabilitating decks and superstructures as needed. The Major Bridge program will not only improve bridge conditions, but it will also enhance transportation system resilience.

Supporting National Goals and Performance of the National Highway System

The investment strategies support progress toward the national goals that include safety, infrastructure condition, congestion reduction, system reliability, freight movement and economic vitality, and environmental sustainability.[2] As mentioned, the investment strategies support these goals by:

- Improving bridge conditions to meet targets and progress toward the SOGR
- Sustaining pavements at targeted levels
- Enhancing resilience by reducing the number of scour-critical structures

- Supporting safety by improving friction and shoulder conditions where they could contribute to crashes
- Sustaining long-term freight mobility by reducing the number of load-limited NHS bridges

Although not part of the investment strategies, an important risk response strategy noted in the Risk Management section was to staff and invest in an enhanced drainage maintenance program. Drainage in good condition can enhance water quality by implementing storm water BMPs. Those efforts will also support the national goal of environmental sustainability.

Monitoring Risks From Inflation

The investment strategy allocations are “finely tuned,” meaning that they include no excess funds or contingencies for inflation beyond the expected 3.5-percent inflation rate. As noted in the Risk Management section, prices at the time this TAMP was developed were rising rapidly. It is possible that construction prices could rise further and exceed the 3.5-percent inflation rate assumed in the allocations. If that occurs, the department may not be able to afford the amount of bridge and pavement projects called for in the lifecycle plan. However, periods of rapid inflation in 2006 and 2007 were followed by price decreases, leading to a long-term average of 3.5 percent annual construction inflation.

The department’s risk-response strategy to unpredictable construction prices will be to:

- Closely monitor bid prices
- Track forecasted price trends reported in national trade publications for key inputs such as steel, cement, and diesel
- Prepare contingency plans for delaying projects or reducing scope items
- Consider if increased use of chip seals or low-cost pavement products could be substituted for pavement resurfacings
- Analyze the long-term impact of delaying some high-cost pavement reconstruction projects

APPENDIX E. FOOTNOTE REFERENCES

Executive Summary

[1]23 U.S.C. § 148.

[2]49 U.S.C. 70202.

[3] U.S. Department of Transportation Active Transportation website at https://www.transportation.gov/mission/health/active-transportation last accessed August 23, 2023.

[4] U.S. Department of Transportation Complete Streets website https://highways.dot.gov/complete-streets last accessed August 23, 2023.

Chapter 1

[1]This document is written on the premise that TAMP investment strategies can be influenced by MTP objectives such as enhancing the urban environment and improving the quality of life. It is written from the assumption that 23 CFR 450.206(c)(4) and other citations encourage or require that States integrate multiple performance plans and programs into the planning process. The document assumes that "integration" is two-way. The MTP influences the TAMP and the TAMP influences the MTP.

[2]U.S. Department of Transportation Active Transportation website accessed August 23, 2023, at https://www.transportation.gov/mission/health/active-transportation

[3]23 CFR 515.7.

[4]FHWA. 2020. *Case Study 7 - Managing Assets Beyond Pavements and Bridges*. Report No. FHWA-HIF-20-092, p. 2. Washington, DC: FHWA. https://www.fhwa.dot.gov/asset/pubs/hif20092.pdf, last accessed Feb. 10, 2023.

[5]23 CFR 515.7.

[6]23 CFR 515.9(a).

[7]23 CFR 515.5.

[8]23 CFR 515.5.

[9]23 CFR 515.9(d)(1).

[10]Massachusetts Department of Transportation. n.d. "Mission Statement" (web page). https://www.mass.gov/orgs/massachusetts-department-of-transportation, last accessed Feb. 10, 2023.

[11]Connecticut Department of Transportation. n.d. "Our Mission" (web page). https://portal.ct.gov/DOT/General/About-Us#:~:text=Our%20Mission,the%20State%20and%20the%20region, last accessed Feb. 10, 2023.

[12]Illinois Department of Transportation. n.d. "Governance: Mission Statement" (web page). https://idot.illinois.gov/about-idot/our-story/governance/, last accessed Feb. 10, 2023.

[13]Ibid.

[14]Connecticut Department of Transportation. n.d. "Our Mission" (web page). https://portal.ct.gov/DOT/General/About-Us, last accessed Feb. 10, 2023.

[15] 23 CFR 515.9(b).

[16]23 CFR 515.9(c).

[17]23 CFR 515.9(f)(4), 23 CFR 515.11(b), 23 CFR 515.13(b)(2).

[18]23 U.S.C. 150(b)

[19]FHWA. 2016. "Asset Management Plans and Periodic Evaluations of Facilities Repeatedly Requiring Repair and Reconstruction Due to Emergency Events." *Final Rule, Federal Register* 81, no. 205: 73210. https://www.federalregister.gov/documents/2016/10/24/2016-25117/asset-management-plans-and-periodic-evaluations-of-facilities-repeatedly-requiring-repair-and, last accessed Feb. 10, 2023.

[20]23 CFR 515.9(h).

[21]23 CFR 450.206(c)(4).

[22]23 CFR 450.208(e).

Chapter 2

[1]Giles, C. G., B. E. Sabey, and K. H. F. Cardew. 1962. "Development and Performance of the Portable Skid-Resistance Tester." *Symposium on Skid Resistance*: 50–74. https://doi.org/10.1520/STP44406S, last accessed February 10, 2023.

[2]Whitehurst, E. A., and W. Goodwin. 1955. "Pavement Slipperiness in Tennessee." *Highway Research Board Proceedings* Volume 34.

[3] Fwa, T.F., Determination and prediction of pavement skid-resistance-connecting research and practice, Journal of Road Engineering, 2021, 43-62

[4]Viner, H. E., A. R. Parry, and R. Sinhal. 2005. *Linking Road Traffic Accidents With Skid Resistance – Recent U.K. Developments, International Conference on Surface Friction of Roads and Runways, Christchurch, New Zealand*. https://www.semanticscholar.org/paper/Linking-road-traffic-accidents-with-skid-recent-UK-Viner-Sinhal/b16a14c5c40b196ada4f76e17ee3f0dc61642020, last accessedFeb. 10, 2023.

[5]23 CFR 515.7(a)(1).

[6]FHWA. 2015. *Evaluation of Pavement Safety Performance*. Report No. FHWA-HRT-14-065. Washington, DC: Federal Highway Administration. https://www.fhwa.dot.gov/publications/research/safety/14065/index.cfm, last accessed February 17, 2023.

[7]FHWA. 2015. *Evaluation of Pavement Safety Performance*. Report No. FHWA-HRT-14-065. Washington, DC: Federal Highway Administration. https://www.fhwa.dot.gov/publications/research/safety/14065/index.cfm, last accessed February 17, 2023.

[8]Chan, C. Y., B. Huang, X. Yan, and S. Richards. 2010a. "Investigating Effects of Asphalt Pavement Conditions on Traffic Accidents in Tennessee Based on the Pavement Management System (PMS)." *Journal of Advanced Transportation* 44, no. 3: 150–61. https://doi.org/10.1002/atr.129, last accessed February 23, 2012

[9]Cenek, P. D., and R. B. Davies. 2004. "Crash Risk Relationships for Improved Safety Management of Roads." Presented at the In Towards Sustainable Land Transport Conference. Wellington, N.Z.: New Zealand Institute of Highway Technology.

[10]Gao, J., K. Gkritza, O. Smadi, N. R. Hawkins, B. A. Bektas, and I. Nlenanya. 2012. *Asset Management and Safety: A Performance Perspective*. MTC Project 2009-01. Ames, Iowa: Midwest Transportation Consortium Institute for Transportation, Iowa State University.

[11]Lee, J., B. H. Nam, and M. Abdel-Aty. 2015. "Effects of Pavement Surface Conditions on Traffic Crash Severity." *Journal of Transportation Engineering* 141 no, 10: 04015020. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000785, last accessed February 10, 2023.

[12]Lee et al. p. 9.

[13]FHWA. 2015. *Evaluation of Pavement Safety Performance*. FHWA-HRT-14-065. Washington, DC: Federal Highway Administration. p6. https://www.fhwa.dot.gov/publications/research/safety/14065/index.cfm, last accessed February 17, 2023.

[14]Li, S., S. Noureldin, Y. Jiang, and Y. Sun. 2012. *Evaluation of Pavement Surface Friction Treatments*. Report No. FHWA/IN/JTRP-1012/04. Indianapolis, IN: Joint Transportation Research Program, Indiana Department of Transportation.

[15]FHWA. 2015. *Evaluation of Pavement Safety Performance*. Report No. FHWA-HRT-14-065. Washington, DC: Federal Highway Administration. p23. https://www.fhwa.dot.gov/publications/research/safety/14065/index.cfm, last accessed February 17, 2023.

[16] FHWA. n.d. “Continuous Pavement Friction Measurement (CPFM)” (webpage).

https://safety.fhwa.dot.gov/roadway_dept/pavement_friction/cpfm/, last accessed March 3, 2023.

[17] FHWA. 2015. Evaluation of Pavement Safety Performance. Report No. FHWA-HRT-14-065. Washington, DC: Federal Highway Administration. p23.

[18]Long, K., H. Wu, Z. Zhang, and M. Murphy. 2014. *Quantitative Relationship between Crash Risks and Pavement Skid Resistance*. Report No. FHWA/TX-13/0-6713-1. Austin, TX: TxDOT. https://rosap.ntl.bts.gov/view/dot/27448, last accessed February 10, 2023.

[19]Owen, Mark. 2014. *An Overview of NZ History with Skid Resistance on the Highway Network*. Wellington, N.Z.: New Zealand Transport Agency.

[20]Zelelew, H., M. Khasawneh, and A. Abbas. 2014. “Wavelet-Based Characterization of Asphalt Pavement Surface Macro-Texture.” *Civil Engineering Faculty Research* 15, no. 3:622–641. https://ideaexchange.uakron.edu/civil_ideas/7/, last accessed February 10, 2023.

[21]Hall, J. W., K. L. Smith, L. Titus-Glover, J. C. Wambold, T. J. Yager, and Z. Rado. 2009. *NCHRP Web-Only Document 108: Guide for Pavement Friction*. p. 26. Washington, DC: National Academies of Sciences, Engineering, and Medicine. https://doi.org/10.17226/23038, last accessed February 10, 2023.

[22]Dave, E. V., R. D. Kostick, and J. Dailey. 2017. “Performance of High Friction Bridge Deck Overlays in Crash Reduction.” *Journal of Performance of Constructed Facilities* 31, no. 2: 04016094. https://doi.org/10.1061/(asce)cf.1943-5509.0000945, last accessed February 10, 2023.

[23]FHWA. 2015. *Evaluation of Pavement Safety Performance*. Report No. FHWA-HRT-14-065. Washington, DC: Federal Highway Administration. https://www.fhwa.dot.gov/publications/research/safety/14065/index.cfm, last accessed February 17, 2023.

[24]Hall, J. W., K. L. Smith, L. Titus-Glover, J. C. Wambold, T. J. Yager, and Z. Rado. 2009. *NCHRP Web-Only Document 108: Guide for Pavement Friction*. p. 11. Washington, DC: National Academies of Sciences, Engineering, and Medicine. https://doi.org/10.17226/23038, last accessed February 10, 2023.

[25]Hall et al.

[26]FHWA. n.d. “About Intersection Safety” (web page). https://highways.dot.gov/safety/intersection-safety/about, last accessed Feb. 10, 2023

[27]FHWA. 2020. *High Friction Surface Treatments at Intersections*. FHWA-SA-20-012. Washington, DC: Federal Highway Administration. https://safety.fhwa.dot.gov/intersection/stop/fhwasa20012.pdf, last accessed March 23, 2023.

[28]Harkey, D. 2016. *National Cooperative Highway Research Program Report 617 Accident Modification Factors for Traffic Engineering and ITS Improvements*, Appendix D. Washington, DC: National Cooperative Highway Research Program.

[29]FHWA. 2021. *High Friction Surface Treatment Site Selection and Installation Guide*. Report No. FHWA-SA-21-093. Washington DC: Federal Highway Administration. https://highways.dot.gov/sites/fhwa.dot.gov/files/2022-06/HFST_Guide_HPA.pdf, last accessed March 3, 2023.

---

[30]Kamel, N., and T. Gartshore. 1982. *Ontario's Wet Pavement Accident Reduction Program*. Presented at Pavement Surface Characteristics and Materials symposium. Orlando, FL: ASTM Committees E-17 on Traveled Surface Characteristics and D-4 on Road and Paving Materials.

[31]Hall, J. W., K. L. Smith, L. Titus-Glover, J. C. Wambold, T. J. Yager, and Z. Rado. 2009. *NCHRP Web-Only Document 108: Guide for Pavement Friction*. p. 66. Washington, DC: National Academies of Sciences, Engineering, and Medicine. https://doi.org/10.17226/23038, last accessed February 10, 2023.

[32]Hall, J. W., K. L. Smith, L. Titus-Glover, J. C. Wambold, T. J. Yager, and Z. Rado. 2009. *NCHRP Web-Only Document 108: Guide for Pavement Friction*. p. 67. Washington, DC: National Academies of Sciences, Engineering, and Medicine. https://doi.org/10.17226/23038, last accessed February 10, 2023.

[33]Stephenson, M., M. Hodgson, and A. Premathilake. 2014. *A Review of the Use of High Friction Surfacing in London*. https://saferroadsconference.com/wp-content/uploads/2016/05/Monday-pm-MA-3-Stephenson_Mark_114_V1_2014127-A-review-of-the-use-of-High-Friction-surfacing-in-London.pdf, last accessed February 10, 2023.

[34]Gou, Z, et al. 2009. "Mixture Design of Pavement Surface Course Considering the Performance of Skid Resistance and Disaster Proof in Tunnels." *Journal of Materials Engineering* 21, no. 4.

[35]FHWA. 2016. *Low-Cost Treatments for Horizontal Curve Safety*. Report No. FHWA-SA-15-084. Washington, DC: Federal Highway Administration.

[36]FHWA. n.d. "The Safety Edge Pavement Edge Treatment" (web page). https://safety.fhwa.dot.gov/roadway_dept/pavement/safedge/brochure/, last accessed February 10, 2023.

[37]Storm, R., S. Klump, O. Kosta, M. Raad, and E. Wemple. 2020. *Rectangular Rumble Strip Safety Evaluation*. Report No. MN 2020-07. Roseville, MN: Minnesota Department of Transportation.

[38]23 U.S.C. § 148(a)(1).

[39]FHWA. n.d. "High-Risk Rural Roads (HRRR)" (web page). https://safety.fhwa.dot.gov/hsip/hrrr/, last accessed February 10, 2023.

[40]FHWA. 2014. *Manual for Selecting Safety Improvements on High-Risk Rural Roads*. Report No. FHWA-SA-14-075. Washington, DC: Federal Highway Administration.

[41]Start, M. R., J. Kim, and W. D. Berg. 1998. "Potential Safety Cost-Effectiveness of Treating Rutted Pavements." *Transportation Research Record: Journal of the Transportation Research Board* 1629, no. 1: 208–13. https://doi.org/10.3141/1629-23, last accessed February 10, 2023.

[42]Guo, X.-X., B.-W. Zhou, and C. Zhang. 2014. *Analysis of Rutting Index for Pavement Maintenance Based on Driving Safety on Surface Gathered Water Consideration*. Reston, VA: American Society of Civil Engineers. https://doi.org/10.1061/9780784413623.087, last accessed February 10, 2023.

[43]Hou, X.-S., S.-L. Ma, and C.-X. Wang. 2007. "Research on Measurement and Evaluation of Asphalt Pavement Rut Based on Traffic Safety." *Journal of Highway and Transportation Research and Development* (English Edition) 2, no. 1: 12–16. https://doi.org/10.1061/JHTRCQ.0000160, last accessed February 10, 2023.

[44]Pierce, L. M., G. McGovern, and K. A. Zimmerman. 2013. *Practical Guide for Quality Management of Pavement Condition Data Collection*. Report No. DTFH61-07-D-00028. Washington, DC: FHWA. https://www.fhwa.dot.gov/pavement/management/qm/data_qm_guide.pdf, last accessed February 10, 2023.

[45]Xu, S. 1994. "Pavement Rutting Depth Related to Vehicle Travel Safety." *Journal of Transportation Engineering* 138, no. 4.

[46]Chan, C.-Y., B. Huang, X. Yan, and S. Richards. 2010a. "Investigating Effects of Asphalt Pavement Conditions on Traffic Accidents in Tennessee Based on the Pavement Management System (PMS)." *Journal of Advanced Transportation* 44, no. 3: 150–61. https://doi.org/10.1002/atr.129, last accessed February 12, 2023.

[47]Chan et al.

[48]FHWA. 2021. *Present Serviceability Rating Computation from Reported Distresses*. Report No. FHWA-HRT-21-041. Washington, DC: Federal Highway Administration.

[49]Al-Masaeid, H. R. 1997. "Impact of Pavement Condition on Rural Road Accidents." *Canadian Journal of Civil Engineering* 24, no. 4: 523–31. https://doi.org/10.1139/L97-009, last accessed February 12, 2023.

[50]Li, Y., C. Liu, and L. Ding. 2013. "Impact of Pavement Conditions on Crash Severity." *Accident Analysis & Prevention* 59, October: 399–406. https://doi.org/10.1016/j.aap.2013.06.028, last accessed February 23, 2023.

[51]Mamlouk, M., M. Vinayakamurthy, B. Underwood, and K. Kaloush. 2018. "Effects of the International Roughness Index and Rut Depth on Crash Rates." *Transportation Research Record* 2672, no. 40.

[52]Karlaftis, M. G., and I. Golias. 2002. "Effects of Road Geometry and Traffic Volumes on Rural Roadway Accident Rates." *Accident Analysis & Prevention* 34, no. 3: 357–65. https://doi.org/10.1016/S0001-4575(01)00033-1, last accessed February 12, 2023.

[53]Gao, J., K. Gkritza, O. Smadi, N. R. Hawkins, B. A. Bektas, and I. Nlenanya. 2012. *Asset Management and Safety: A Performance Perspective*. Report No. MTC Project 2009-01. Ames, IA: Midwest Transportation Consortium Institute for Transportation, Iowa State University.

[54]FHWA. n.d. "What Are CMFs," accessed at the "Crash Modification Factors Clearinghouse" (web page). Washington, DC: FHWA. https://www.cmfclearinghouse.org/, last accessed February 17, 2023.

[55]FHWA. 2020. *Developing Crash-Modification Factors for High-Friction Surface Treatments*. Report No. FHWA-HRT-20-061. Washington, DC: Federal Highway Administration. https://www.fhwa.dot.gov/publications/research/safety/20061/20061.pdf , last accessed March 3, 2023.

[56]FHWA. 2015. *Evaluation of Pavement Safety Performance*. Report No. FHWA-HRT-14-065. Washington, DC: Federal Highway Administration. https://www.fhwa.dot.gov/publications/research/safety/14065/index.cfm, last accessed February 20, 2023.

[57]National Highway Traffic Safety Administration. n.d. "Traffic Safety Facts Annual Report Tables" (web page). https://cdan.nhtsa.gov/tsftables/tsfar.htm#, last accessed February 13, 2013.

[58]Based update data from the Fatality Analysis Reporting System (FARS).

[59]FHWA. 2021. "National Highway System Road Length – 2020, Table HM-40, Highway Statistics 2020" (web page). https://www.fhwa.dot.gov/policyinformation/statistics/2020/hm40.cfm, last accessed March 23, 2023.

[60]Atlanta Regional Commission. n.d. *Safe Streets for Walking & Bicycling*, p. 29.

[61]Metropolitan Council. n.d. "Regional Pedestrian Safety Action Plan" (web page). https://metrocouncil.org/Transportation/Planning-2/Reports/Bike-Pedestrian-Planning/Regional-Pedestrian-Safety-Action-Plan.aspx, last accessed February 12, 2023.

[62]Indianapolis Metropolitan Planning Organization. 2020. *Regional Pedestrian Plan*, p. 60.

[63]Gantz, T., E. J. De La Garza, D. R. Ragland, and L. Cohen. 2003. *Traffic Safety in Communities of Color*. Berkeley, CA: University of California Safe Transportation Research and Education Center. https://escholarship.org/uc/item/1m07078c, last accessed February 12, 2023.

[64]Rodriguez, M., S. Sklar, and H. Zaccaro. 2018. *Dangerous by Design, Statistically Speaking: Pedestrian Fatalities and Urban Design*. Washington, DC: Smart Growth America.

[65]Rebentisch, H., R. Wasfi, and D. Piatkowski. 2019. "Safe Streets for All? Analyzing Infrastructural Response to Pedestrian and Cyclist Crashes in New York City, 2009-2018." *Transportation Research Record: Journal of the Transportation Research Board* 2673, no. .2.

[66]Goldberg, H. 2001. *State and County Supported Car Ownership Program Programs Can Help Low-Income Families Secure and Keep Jobs, Center on Budget and Policy Priorities*. Washington, DC: Center on Budget and Policy Priorities.

[67]Loukatou-Sideris, A., R. Ligget, and H. Sung. 2005. "Death on the Crosswalk: A Study of Pedestrian-Automobile Collisions in Los Angeles." *Journal of Planning Education and Research* 26, no. 3.

[68]Pei-Sung, L., G. Rui., E. Bialkowska-Jelinska, A. Kourtellis, and Y. Zhang. 2019. "Development of Countermeasures to Effectively Improve Pedestrian Safety in Low-Income Areas." *Journal of Transportation Engineering* 6, no. 2.

[69]Rodriquez et al.

[70]Cottrill, C., and T. Piyushimita. 2009. "Evaluating Pedestrian Crashes in Areas With Low-Income or Minority Populations." *Accident Analysis & Prevention* 42, no. 6.

[71]Zhang, L., S. Ghader, A. Asadabadi, M. Franz, C. Xiong, and J. Litchford. 2017. *Analyzing the Impact of Median Treatments on Pedestrian/Bicyclist Safety*. Report No. MD-17-SHA/UM/4-28. Baltimore, MD: Maryland State Highway Administration.

[72]FHWA. 2008. *FHWA Desktop Reference for Crash Reduction Factors*. Report No. FHWA-SA-08-011, Table 11. Washington, DC: FHWA.

[73]FHWA. 2008. *FHWA Desktop Reference for Crash Reduction Factors*. Report No. FHWA-SA-08-011, Table 11. Washington, DC: FHWA.

[74]FHWA. n.d. *Crosswalk Visibility Enhancements*. Report No. FHWA-SA-21-049. Washington, DC: FHWA. https://safety.fhwa.dot.gov/provencountermeasures/crosswalk-visibility.cfm, last accessed February 12, 2023.

Chapter 3

[1]Bennett, C. R., and I. D. Greenwood. 2003a. *HDM-4 Calibration Reference Manual*. Volume 5. International Study of Highway Development and Management Tools (ISOHDM), World Road Association (PIARC), ISBN 2-84060-103-6. Paris, France, World Road Association.

[2]World Bank. n.d. "World Bank Road Software Tools" (web page). https://collaboration.worldbank.org/content/sites/collaboration-for-development/en/groups/world-bank-road-software-tools/files.asset.html/content/usergenerated/asi/cloud/content/sites/collaboration-for-development/en/groups/world-bank-road-software-tools/files/jcr:content/content/primary/library1/hdm4ruc_version_50-LM5v.html, last accessed February 12, 2023.

[3]23 CFR 490.313(b)(1)(i)-(iii).

[4]23 CFR 515.9(d)(1).

[5]World Health Organization. 2019. *Environmental Noise Guidelines for the European Region*, p. 2. ISBE 978 92 890 5356 3. Copenhagen, Denmark: World Health Organization.

[6]Hänninen, O., A. B. Knol, M. Jantunen, T .A. Lim, A. Conrad, M. Rappolder. P. Carrer, A. C. Fanetti, R. Kim, J. Buekers, R. Torfs, I. Iavarone, T. Classen, C. Hornberg, and O. C. Mekel. EBoDE Working Group. 2014. "Environmental Burden of Disease in Europe: Assessing Nine Risk Factors in Six Countries." *Environmental Health Perspective* 122, no. 5:439–446. http://dx.doi.org/10.1289/ehp.1206154, last accessed February 12, 2023.

[7]Ozdenerol, E., Y. Huang, F. Javadnejad, and A. Antipoval. 2015. "The Impact of Noise on Housing Values." *Journal of Real Estate Practice and Education* 18, no. 1.

[8]Guijarro, F. 2019. "Assessing the Impact of Road Traffic Externalities on Residential Price Values: A Case Study in Madrid Spain." *International Journal of Environmental Research and Public Health* 16, no. 24:5149.

[9]Wilhelmsson, M. 2000. “The Impact of Traffic Noise on the Values of Single-Family Houses.” *Journal of Environmental Planning and Management* 43, no. 6: 799–815.

[10]FHWA. 2007. *The Little Book of Quieter Pavements*. Report No. FHWA-IF-08-004. Washington, DC: FHWA.

Chapter 4

[1]FHWA. 2019. “National List of Major Freight Highway Bottlenecks and Congested Corridors Federal Highway Administration (FHWA) Freight Mobility Trends: Truck Hours of Delay, 2019” (web page) https://ops.fhwa.dot.gov/freight/freight_analysis/mobility_trends/national_list_2020.pdf, last accessed August 26, 2023.

[2]FHWA. n.d. “Tables of Frequently Requested NBI Information” (web page). https://www.fhwa.dot.gov/bridge/britab.cfm, last accessed February 12, 2023.

[3] 23 CFR 661.5

[4]FHWA. 2020. “FHWA Bridges on the NHFN.” *Status of the Nation's Highways, Bridges, and Transit Conditions and Performance:* 23rd Edition: Part III: Highway Freight Transportation - Report to Congress.

[5]USDOT. n.d. “Freight Analysis Framework Version 4 (FAF4)” Data Tabulation Tool (web page). https://www.bts.gov/faf/faf4, last accessed February 12, 2023.

[6]Percentage derived from reviewing FHWA Highway Statistics 2018 Tables HM-60 Estimated Lane-Miles by Functional System, Table HM-43 National Highway System Lane-Miles by functional system, Table VM-2 Vehicle-miles of travel, by functional system, and Table HM-44 Vehicle miles of travel by functional system.

[7]FHWA. 2020. “Table VM-1” Annual Vehicle Distance Traveled in Miles and Related Data 2020 by Highway Category and Vehicle Type (web page). https://www.fhwa.dot.gov/policyinformation/statistics/2020/vm1.cfm, last accessed February 12, 2023.

[8]FHWA. 2023. *National Strategic Freight Plan*, p. 40. Washington, DC: FHWA at https://www.transportation.gov/freight/NFSP last accessed August 26, 2023.

[9] Department of Transportation Guidance on Multimodal State Freight Plans and State Freight Advisory Committees, accessed at https://www.transportation.gov/sites/dot.gov/files/2023-01/State%20Freight%20Plan%20and%20State%20Freight%20Advisory%20Committee%20Guidance_signed.pdf August 26, 2023.

[10]23 CFR Part 450.

[11]23 CFR Part 490.

[12]FHWA. 2015. *Federal Highway Administration Environmental Justice Reference Guide*. p.10. www.kipda.org/wp-content/uploads/2021/01/FHWA_EJ_Guide_2015.pdf, last accessed February 12, 2023.

[13]FHWA. 2015. *Guidelines for the Visual Impact Assessment of Highway Projects*. Report No. FHWA-HEP-15-029. Washington, DC: FHWA. https://blmwyomingvisual.anl.gov/docs/VIA_Guidelines_for_Highway_Projects.pdf, last accessed February 12, 2023.

[14]FHWA. 2015. *Guidelines for the Visual Impact Assessment of Highway Projects*.

[15]Minnesota Department of Transportation, 1995. *Aesthetic Guidelines for Bridge Design*. St. Paul, MN: Minnesota Department of Transportation.

[16]Utah Department of Transportation. 2014. *Utah Department of Transportation, UDOT Aesthetics Guidelines*. Salt Lake City, UT: Utah Department of Transportation.

[17]Maryland State Highway Administration. 2015. *Aesthetic Bridges - Users Guide*. Baltimore, MD: Maryland State Highway Administration.

[18]North Carolina Department of Transportation. 2015. *North Carolina Department of Transportation Aesthetics Guidance Manual*.

Chapter 5

[1]McNeil, S., E. Lee, Y. Li, R. Chiquoine, K. Heaslip, and G. Herning. 2019. *Collaborative Proposal: The Connection between State of Good Repair and Resilience: Measures for Pavements and Bridges*. Report No. CAIT-UTC-NC 45. Piscataway, NJ: Center for Advanced Infrastructure and Transportation, Rutgers, The State University of New Jersey.

[2]Bocchini, P., D. M. Frangopol. 2012. "Optimal Resilience- and Cost-Based Postdisaster Intervention Prioritization for Bridges along a Highway Segment." *Journal of Bridge Engineering* 17, no. 1: 117–29. https://doi.org/10.1061/(ASCE)BE.1943-5592.0000201, last accessed February 12, 2023.

[3]FHWA. n.d. "Resilience Pilots" (web page). https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/, last accessed February 12, 2023.

[4]FHWA. 1991. "Technical Advisory Evaluating Scour at Bridges" (web page). https://www.fhwa.dot.gov/engineering/hydraulics/policymemo/t514023.cfm, last accessed February 12, 2023.

[5]FHWA. 2006. *Seismic Retrofitting Manual for Highway Structures: Part 1 – Bridges*. Publication No. FHWA-HRT-6-032. Washington, DC: FHWA.

[6]FHWA. n.d. "Resilience Pilots" (web page). https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/, last accessed February 12, 2023.

[7]FHWA. 2016. *Highways in the River Environment – Floodplains, Extreme Events, Risk, and Resilience*. Publication No. FHWA-HIF-16-018. Washington, DC: FHWA.

[8]FHWA. 1995. *Recording and Code Guide for the Structure Inventory and Appraisal of the Nation's Bridges*. Publication No. FHWA-PD-96-001. Washington, DC: FHWA.

[9]FHWA. 2012. *Guidance on Applying Risk Based, Data Driven Decision-Making Process to the FHWA Scour Program*. Washington, DC: FHWA.

[10]FHWA. 2006. S*eismic Retrofitting Manual for Highway Structures: Part 1 – Bridges*. Publication No. FHWA-HRT-06-032. Washington, DC: FHWA.

[11]Sturdevant Rees, P., S. Jackson, and S. Mabee. 2018. *A Proposed Method for Assessing the Vulnerability of Road-Stream Crossings to Climate Change, Deerfield River Watershed Project*. Boston, MA: Massachusetts Department of Transportation.

[12]Minnesota Department of Transportation. 2014. *MnDOT Flash Flood Vulnerability and Adaptation Assessment Pilot Project*. St. Paul, MN: Minnesota Department of Transportation.

[13]Kentucky Transportation Cabinet. 2019. *Asset Management, Extreme Weather, and Proxy Indicators, Final Report*. Frankfort, KY: Kentucky Transportation Cabinet.

[14]FHWA. 2016. *Hydraulic Engineering Circular No. 17, 2nd Edition, Highways in the River Environment – Floodplains, Extreme Events, Risk, and Resilience*. Publication No. FHWA-HIF-16-018. Washington, DC: FHWA.

[15]Ibid p. 6-11.

[16]Wardhana, K., and F. Hadipriono. 2003. "Analysis of Recent Bridge Failures in the United States." *Journal of Constructed Facilities 17*, no. 3.

[17]National Highway Traffic Safety Administration. n.d. "Traffic Safety Facts Annual Report Tables" (web page). https://cdan.nhtsa.gov/tsftables/tsfar.htm#, last accessed February 12, 2023.

[18]Ortiz, F. 2020. "Coming Back from Disaster." *Public Roads* 83, no. 4.

[19]Anderson, I., J. Hanley, D. Rizzo, and D. Huston. 2020. "Evaluating Damage to Vermont Bridges by Hurricane Irene with Multivariate Bridge Inspection and Stream Hydrogeologic Data." *Journal of Bridge Engineering* 25, no. 10.

[20]Kim. Y., W. Marshall, and K. Pal. 2014. "Assessment of Infrastructure Devastated by Extreme Floods: A Case Study From Colorado, USA." *Civil Engineering*, 167, no. CE4.

[21]Padgett, J. et al. 2008. "Bridge Damage and Repair Costs from Hurricane Katrina." *Journal of Engineering* 13, no. 1.

[22]Anderson et al.

[23]Padgett, J., R. Desroches, O. Kwon, and N. Burdette. 2008. *Bridge Damage and Repair Costs from Hurricane Katrina, Journal of Bridge Engineering* 13, no. 1.

[24]Transportation Research Board of the National Academies of Sciences, Engineering, and Medicine. 2017. *Bridge Scour Risk Management*. Washington, DC: Transportation Research Board of the National Academies of Sciences, Engineering, and Medicine.

[25]FHWA. 2015. *Tech Brief, Climate Change Adaptation for Pavements*. Publication No. FHWA-HIF-15-015. Washington, DC: FHWA.

[26]British Columbia Ministry of Municipal Affairs. 2018. *Climate Change and Asset Management, A Sustainable Service Delivery Primer*. Asset Management, B.C.

[27]FHWA. 2015. *Climate Change Adaptation for Pavements*. Publication No. FHWA-HIF-15-015. Washington, DC: FHWA.

[28]Meyer, M. et al. 2014. *Strategic Issues Facing Transportation, Volume 2, Climate Change and Extreme Weather Events and the Highway System*. . NCHRP Report 750. Washington, DC: Transportation Research Board of the National Academies of Sciences, Engineering, and Medicine.

[29]World Road Association. 2015. *International Climate Change Adaptation Framework for Road Infrastructure*. Paris, France: World Road Association.

[30]FHWA. 2016. *Impact of Environmental Factors on Pavement Performance in the Absence of Heavy Loads*. Publication No. FHWA-HRT-16-078. Washington, DC: FHWA.

[31]TxDOT. 2019. *Asset Management, Extreme Weather, and Proxy Indicators Pilot Final Report*.

[32]Knott, J. et al. 2018. "Adaptation Planning to Mitigate Coastal-Road Pavement Damage from Groundwater Rise Caused by Sea-Level Rise." *Transportation Research Record* 2672, no. 2.

[33]Stoner, A. et al. 2019. "Quantifying the Impact of Climate Change on Flexible Pavement Performance and Lifetime in the United States." *Transportation Research Record* 2673, no: 1.

[34]Dylla, H., and R. Hyman. 2018. *FHWA Boosting Pavement Resilience*. *Public Roads* 82, no. 3.

[35]Meagher, W. et al. 2012. "Method for Evaluating Implications of Climate Change for Design and Performance of Flexible Pavements." *Transportation Research Record* 2305, no. 1.

[36]Underwood, B. S., Z. Guido, P. Gudipudi, and Y. Feinberg. 2017. "Increased Costs to US Pavement Infrastructure From Future Temperature Rise." *Nature Climate Change* 7 no. 10: 704.

[37]Underwood, B. S., Z. Guido, P. Gudipudi, and Y. Feinberg. 2017. "Increased Costs to US Pavement Infrastructure From Future Temperature Rise." *Nature Climate Change* 7 no. 10: 704.

[38]Maryland Department of Transportation State Highway Administration. 2019. *Integrating Extreme Weather and Climate Risk into MDOT SHA Asset Management and Planning, Final Report*. Baltimore, MD: Maryland Department of Transportation.

[39]Swarna, S. et al. 2021. “Assessing Climate Change Impact on Asphalt Binder Grade Selection and its Implications.” *Transportation Research Record* 2675, no. 1.

[40]Qiao, Y., et al. 2020. “Climate change impacts on asphalt road pavement construction and maintenance.” *Journal of Industrial Ecology* 24, no. 2.

[41]Qiao et al.

[42]Guest, G. et al. 2020. “Incorporating the Impacts of Climate Change into Infrastructure Life Cycle Assessments.” *Journal of Industrial Ecology* 24, no. 2.

[43]FHWA. 2015. *Tech Brief, Climate Change Adaptation for Pavements*. FHWA-HIF-15-015. Washington, DC: FHWA.

[44]Knott, J. et al. 2018. “Adaptation Planning to Mitigate Coastal-Road Pavement Damage from Groundwater Rise Caused by Sea-Level Rise.” *Transportation Research Record* 2672, no. 2.

[45]Guest, G. et al. 2020. A Case Study of Pavement Service Life Performance.” *Journal of Industrial Ecology* 24, no. 2.

[46]Knott, J. 2019. “Seasonal and Long-term Changes to Pavement Life Caused by Rising Temperatures from Climate Change.” *Transportation Research Record* 2673, no. 6.

[47]FHWA. 2017. *Vulnerability Assessment and Adaptation Framework*, Third Edition. Publication No. FHWA-HEP-18-020.Washington, DC: FHWA.

[48]FHWA. 2020. *Climate Resilience Pilot Program, Arizona Department of Transportation*. Publication No. FHWA-HEP-16-038. Washington, DC: FHWA.

Chapter 6

[1]Wyant, D. 2022. *Assessment and Rehabilitation of Existing Culverts*. NCHRP Synthesis 303. Transportation Research Board, The National Academies of Sciences, Engineering, and Medicine.

[2]FHWA. 2007. *Culvert Management Systems, Alabama, Maryland, Minnesota, and Shelby County*. Publication No. FHWA-IF-07-032. Washington, DC: FHWA.

[3]Cedergren, H. 1988. “Why All Important Pavements Should be Well Drained.” *Transportation Research Record* 1188.

[4]American Society of Civil Engineers. 2022. “John Loudon McAdam” (web page). https://www.asce.org/about-civil-engineering/history-and-heritage/notable-civil-engineers/john-loudon-mcadam, last accessed February 12, 2023.

[5]Engineering Rome. 2023. “Ancient Roman Roads and Their Influence on Modern Road Designs” (web page). http://engineeringrome.org/ancient-roman-roads-and-their-influence-in-modern-road-designs/, last accessed February 12, 2023.

[6]The Asphalt Institute. n.d. “Proper Drainage ensures lasting asphalt pavement structures” (web page). http://asphaltmagazine.com/proper-drainage-ensures-lasting-asphalt-pavement-structures/, last accessed February 12, 2023.

[7]FHWA. 2020. *Summary Report, Use of LTPP SMP Data to Quantify Moisture Impacts on Fatigue Cracking in Flexible Pavements*. Publication No. FHWA-HRT-20-006. Washington, DC: FHWA.

[8] Forsythe, R. et al. 1987. “Economic Impact of Pavement Surface Drainage.” *Transportation Research Record* 1121.

[9]Arika, C. et al. 2009. *Subsurface Drainage Manual for Pavements in Minnesota*. Report No. MN/RC 2009-17. St. Paul, MN: Department of Bioproducts and Biosystems Engineering, University of Minnesota.

[10]Arika, C. et al. 2009. *Subsurface Drainage Manual for Pavements in Minnesota*. Report No. MN/RC 2009-17. St. Paul, MN: Department of Bioproducts and Biosystems Engineering, University of Minnesota.

[11]Christopher, B., and V. McGuffrey. 1997. *Pavement Subsurface Drainage Systems, Synthesis of Highway Practice, 239*. Washington, DC: National Academy Press.

[12]Ibid, p. 2.

[13]Ibid, p. 2.

[14]Mumum, M., and S. Haider. *Use of LTPP SMP Data to Quantify Moisture Impacts on Fatigue Cracking in Flexible Pavements*. Publication No. FHWA-HRT-20-006. Washington, DC: FHWA.

[15]Arika, C. et al. 2009. *Subsurface Drainage Manual for Pavements in Minnesota*. Report No. MN/RC 2009-17. St. Paul, MN: Department of Bioproducts and Biosystems Engineering, University of Minnesota.

[16]FHWA. 2020. *Use of LTPP SMP Data to Quantify Moisture Impacts on Fatigue Cracking in Flexible Pavements*. Publication No. FHWA-HRT-20-006.

[17]Arampamoorthy, P. et al. 2014. *Optimizing Drainage Maintenance for Pavement Performance*. Wellington, New Zealand: New Zealand Transport Agency.

[18]Li, Q. L. Mills and S. McNeil. 2011. *The Implications of Climate Change on Pavement Performance and Design, A Report submitted to the University of Delaware Transportation Center*.

[19]Qiao, Y, et al. 2020. "Flexible Pavements and Climate Change: A Comprehensive Review and Implications." *Sustainability* 12, no. 1057.

[20]Transportation Research Board. 1997. *Pavement Subsurface Drainage Systems, A Synthesis of Highway Practice*. NCHRP Synthesis 96, p. 3. Washington, DC: Transportation Research Board.

[21]FHWA. 2009. *Maintenance of Drainage Features for Safety, A Guide for Local Street and Highway Maintenance Personnel*. Publication No. FHWA-SA-09-024. Washington, DC: FHWA.

[22]FHWA. n.d. "Environmental Review Toolkit" "Stormwater Best Management Practices in an Ultra-Urban Setting: Selection and Monitoring" (web page). https://www.environment.fhwa.dot.gov/Env_topics/water/ultraurban_bmp_rpt/uubmp1.aspx#s11, last accessed February 12, 2023.

[23]U.S.C. § 150(b)(6).

[24]23 CFR 515.9(d)(1).

[25]Maryland.gov. n.d. "Maryland State Highway Administration Mission Statement" (web page). https://roads.maryland.gov/mdotsha/pages/Index.aspx?PageId=83#:~:text=To%20provide%20a%20safe%2C%20well,Maryland's%20communities%2C%20economy%20and%20environment, last accessed February 12, 2023.

[26]Florida Department of Transportation. n.d. "Mission, Vision, and Values" "Our Mission" (web page). https://www.fdot.gov/info/moredot/mvv.shtm, last accessed February 12, 2023.

[27]Connecticut Department of Transportation. n.d. "Mission, Vision & Values" "Vision" (web page). https://www.codot.gov/about/mission-and-vision.html, last accessed February 12, 2023.

[28]FHWA. 2013. "FHWA Hydraulic Engineering Circular No. 22, Third Edition." *Urban Drainage Design Manual*. Publication No. FHWA-NHI-10-009. Washington, DC: FHWA.

[29]FHWA. 2013. "FHWA Hydraulic Engineering Circular No. 22, Third Edition." *Urban Drainage Design Manual*. Publication No. FHWA-NHI-10-009: 7–30. Washington, DC: FHWA., U.S. Department of Transportation Federal Highway Administration.

Chapter 7

[1]FHWA, "Complete Streets" (website). https://www.transportation.gov/mission/health/complete-streets, last accessed February 12, 2023.

[2]Atlanta Regional Commission. n.d. *Safe Streets For Walking & Bicycling: A Regional Action Plan for Reducing Traffic Fatalities in Metropolitan Atlanta*. https://cdn.atlantaregional.org/wp-content/uploads/arc-safe-streets-webview-revmar19-1.pdf, last accessed February 12, 2023.

[3]Atlanta Regional Commission. 2016. *Safe Streets for Walking & Bicycling: A Regional Action Plan*, p. 53.

[4]Northeast Ohio Areawide Coordinating Agency. 2015. "Regional Strategic Plan" "Goal 5: Enhance quality of life in Northeast Ohio" (web page). https://www.noaca.org/regional-planning/major-planning-documents/regional-strategic-plan, last accessed Feburary 12, 2023.

[5]DRCOG, 2019. *Denver Regional Active Transportation Plan*, p. 4. https://drcog.org/sites/default/files/resources/DRCOG_ATP.pdf, last accessed February 12, 2023.

[6]DRCOG. 2019. *Denver Regional Active Transportation Plan*, p. 36. https://drcog.org/sites/default/files/resources/DRCOG_ATP.pdf, last accessed February 12, 2023.

[7]DRCOG. 2019. *Denver Regional Active Transportation Plan*, p. 60. https://drcog.org/sites/default/files/resources/DRCOG_ATP.pdf, last accessed February 12, 2023.

[8]Schneider, R. J. 2018. "Complete Streets Policies and Eliminating Pedestrian Fatalities." *American Journal of Public Health* 108, no. 4: 431–433.

[9]Buelhler, R., and J. Pucher. 2017. "Trends in Walking and Cycling Safety: Recent Evidence from High-Income Countries, With a Focus on the United States and Germany." *American Journal of Public Health* 107, no. 2.

[10]Rettig, R., et al. 2003. "A Review of Evidence-Based Traffic Engineering Measures Designed to Reduce Pedestrian-Motor Vehicle Crashes." *American Journal of Public Health* 92, no. 9.

Chapter 8

[1]Yu, B. and Q. Lu. 2014. "Empirical Model of Roughness Effect on Vehicle Speed." *International Journal of Pavement Engineering* 15, no. 4: 345–351.

[2]Anund, A. 1992. *Road Surface Influence on Speed*. Publication No. Nr. 680-1992, p. ii. Stockholm, Sweden: Swedish Road and Traffic Research Institute.

[3]Sekhar, S., and V. Verghase. 2020. "Influence of Pavement Condition on Headway and Average Travel Speed." *National Conference on Innovations in Engineering & Technology (NCIET)*. Palakkad, India: International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering.

[4]Wu, L. X., and G. Z. Cheng. 2012. "Influence of Damaged Pavement on Saturated Headway and Average Travel Speed of Urban Road Section." *Advanced Materials Research* 446–449: 2453–56. https://doi.org/10.4028/www.scientific.net/AMR.446-449.2453, last accessed February 12, 2023.

[5]Ben-Edigbe, J., and N. Ferguson. 2005. "Extent of Capacity Loss Resulting from Pavement Distress." *Proceedings of the Institution of Civil Engineers - Transport* 158, no. 1: 27–32. https://doi.org/10.1680/tran.2005.158.1.27, last accessed February 12, 2023.

[6]Mucka, P. 2020. "International Roughness Index Thresholds Based on Whole-Body Vibration in Passenger Cars." *Transportation Research Record* 2675: 305–320.

[7]Yu, J., Eddie Chou, Jhy-Tyng Yau. 2006. "Development of Speed-Related Ride Quality Thresholds Using International Roughness Index." *Transportation Research Record* 1974, no. 1.

[8]Abudinen, D., L. Fuentes, J. Carvajal. 2017. "Travel Quality Assessment of Urban Roads Based on International Roughness Index, Case Study in Columbia." *Transportation Research Record* 2612, no. 1: 10.

[9]Jia, Y., S. Wang, J. Peng, Y. Gao, D. Hu, and X. Zhao. 2022. "Evaluation of Pavement Rutting Based on Driving Safety of Vehicles." *International Journal of Pavement Research and Technology* 15.2: 457–469.

[10]23 CFR 490.313(b)(3)(i)(c).

[11]FHWA. 2019. *Does Travel Time Reliability Matter?* Report No. FHWA-HOP-19-062. Washington, DC: FHWA.

[12]FHWA. 2019. *Does Travel Time Reliability Matter?* Report No. FHWA-HOP-19-062. Washington, DC: FHWA.

[13]NCHRP. 2011. *Consequences of Delayed Maintenance*. Publication No. NCHRP 14-20. Washington, DC: National Cooperative Highway Research Program.

[14]Fries, R., T. Anjuman, and M. Chowdhury. 2013. "Selecting an Asset Management System for Intelligent Transportation Systems." *Public Works Management & Policy* 18, no. 4:16.

[15]Anjuman, T. 2009. "Evaluation of an Online Intelligent Transportation System (ITS) Asset Management System." Master's thesis. Clemson University.

[16]FHWA. 2022. *Applying Transportation Asset Management to Intelligent Transportation Systems: A Primer*. Report No. FHWA-HOP-20-047. Washington, DC: FHWA.

[17]Daniels, G., and T. Starr. 1997. "Guidelines for Funding Operations and Maintenance of Intelligent Transportation Systems/Advanced Traffic Management Systems." *Transportation Research Record: Journal of the Transportation Research Board* 1588, no. 1.

[18]Daniels, G., and T. Starr. 1997. "Guidelines for Funding Operations and Maintenance of Intelligent Transportation Systems/Advanced Traffic Management Systems." *Transportation Research Record: Journal of the Transportation Research Board* 1588, no. 1.

[19]Patel, K. 2005. *Intelligent Transportation Systems (ITS) Operational Support Contracts*. Brooklyn, NY: Transportation Research Center, Polytechnic University. https://rosap.ntl.bts.gov/view/dot/16160, last accessed February 12, 2023.

Chapter 9

[1]FHWA. 2018. Questions and Answers (Q&As)" (web page). https://www.fhwa.dot.gov/asset/guidance/faqs.cfm, last accessed February 12, 2023.

[2]FHWA. 2016. 23 CFR Parts 515 and 667, Docket No. FHWA-2013-0052. Federal Register 81, no. 205. p73216.

[3]FHWA. 2018. Questions and Answers (Q&As)" Answer 2 (web page). https://www.fhwa.dot.gov/asset/guidance/faqs.cfm, last accessed February 12, 2023.

[4]23 CFR 515.9(f)(4).

[5]23 CFR 515.9 (f).

[6]23 CFR 515.5.

[7]FHWA. 2018. "Questions and Answers (Q&As)" Answer 34 (web page). https://www.fhwa.dot.gov/asset/guidance/faqs.cfm, last accessed February 12, 2023.

[8] https://www.transportation.gov/mission/health/Safe-Routes-to-School-Programs

[9]FHWA. 2019. *Using an LCP (Life Cycle Planning Process to Support Transportation Asset Management: A Handbook on Putting The Federal Guidance into Practice*. Publication No. FHWA-HIF-19-006. Washington, DC: FHWA.

[10]FHWA. 2019. *Using an LCP (Life Cycle Planning) Process to Support Transportation Asset Management: A Handbook on Putting The Federal Guidance into Practice*. Publication No. FHWA-HIF-19-006, p. 3. Washington, DC: FHWA.

[11]FHWA. 2019. *Using an LCP (Life Cycle Planning) Process to Support Transportation Asset Management: A Handbook on Putting The Federal Guidance into Practice*. Publication No. FHWA-HIF-19-006, p. 15. Washington, DC: FHWA.

Appendix A

[1]FHWA. Forthcoming. *How Pavement and Bridge Conditions Affect Transportation System Performance*. Report No. FHWA-HOP-22-077.

[2]23 CFR 515.7(a) and 23 CFR 515.7(a)(2).

[3]23 CFR 515.7(c)(1-6)

[4]23 CFR 515.9(f)(2).

Appendix B

[1]23 U.S.C. 148(a)(12).

[2]23 CFR 490.607, also called the Truck Travel Time Reliability (TTTR) Index.

[3]23 CFR 490.707

[4]490.507(a)(1)(2).

[5]23 CFR 490.105(c)(1)(2)(3) and 23 U.S.C. 490.105(e).

[6]23 CFR 515.9(f)(1).

[7]U.S.C. 23 119 (e)(4)(d).

[8]FHWA. 2016. 23 CFR Parts 515 and 667. "Asset Management Plans and Periodic Evaluations of Facilities Repeatedly Requiring Repair and Reconstruction Due to Emergency Events." *Federal Register* 81, no. 205. p 73210.

[9]23 CFR 409.307(a)(1-4) and 490.407(c)(1)(2).

[10]23 CFR 490.315(a).

[11]23 CFR 490.411(a).

[12]23 CFR 490.105(c)(1)(2)(3).

[13]FHWA. 2020. *2020 National List of Major Freight Highway Bottlenecks and Congested Corridors Federal Highway Administration (FHWA) Freight Mobility Trends: Truck Hours of Delay*. https://ops.fhwa.dot.gov/freight/freight_analysis/mobility_trends/national_list_2020.htm last accessed February 12, 2023.

[14]Stoner, A. et al. 2019. "Quantifying the Impact of Climate Change on Flexible Pavement Performance and Lifetime in the United States." *Transportation Research Record* 2673, no. 1.

[15]FHWA. 2018. "FHWA Boosting Pavement Resilience." *Public Roads* 82, no. 3. Washington, DC: FHWA.

[16]FHWA. 1995. *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges*. Publication No. FHWA-PD-96-001, p. 75. Washington, DC: FHWA.

[17] 23 CFR 490.111(a)

[18]23 CFR 490.315(a)(b) and 490.411(a)**.**

Appendix C

[1]23 CFR 515.5.

[2]FHWA. 2017. *Incorporating Risk Management Into Transportation Asset Management Plans*. Washington, DC: Federal Highway Administration. https://www.fhwa.dot.gov/asset/pubs/incorporating_rm.pdf, last accessed February 12, 2023.

[3]FHWA. 1995. *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges*. Publication No. FHWA-PD-96-001. Washington, DC: FHWA.

[4]23 CFR 490.409(c).

[5]FHWA. 2022. *Specifications for the National Bridge Inventory*. Publication No. FHWA-HIF-22-017, p. 268. Washington, DC: FHWA.

[6]23 CFR 515.7(c)(4)(5).

[7]23 CFR Part 667.

Appendix D

[1]CFR 515.5, 23 CFR 515.7(e), 23 CFR 515.9(g).

[2]23 U.S.C. § 150(b).