Reformulated Pavement Remaining Service Life Framework

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FOREWORD

Many important decisions are necessary in order to successfully provide and manage a pavement network. At the heart of this process is the prediction of needed future construction events. One approach to providing a single numeric on the condition of a pavement network is the use of pavement remaining service life (RSL). However, many issues exist with the current RSL terminology and resulting numeric that complicate proper interpretation, interagency data exchange, and use. A major source of uncertainty in the current RSL definition is the use of the term "life" to represent multiple points in the pavement construction history. The recommended path to consistency involves adopting terminology of time remaining until a defined construction treatment is required (i.e., RSL is replaced by remaining service interval (RSI)). The term "RSI" has the ability to unify the outcome of different approaches to determine needs by focusing on when and what treatments are needed and the service interruption created. This report presents the framework for replacing the current RSL terminology with one based on more exact construction event terms. It provides detailed information on the research performed concerning remaining pavement life. It explores many issues that exist with the current RSL terminology that complicate proper interpretation, interagency data exchange, and use. While this report focuses on pavements, it is also applicable to other types of transportation infrastructure. A companion document provides step-by-step guidelines for implementing the RSI terminology.(1) This report is intended for use by pavement managers and pavement investment decisionmakers across the United States.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ABBREVIATIONS

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt concrete
ADT	Average daily traffic
ESAL	Equivalent single-axle load
FN	Friction number
FHWA	Federal Highway Administration
FWD	Falling weight deflectometer
HERS	Highway Economic Requirements System
HMA	Hot mix asphalt
HPMS	Highway Performance Monitoring System
IRI	International Roughness Index
JPCP	Jointed plain concrete pavement
LCC	Life-cycle cost
LCCA	Life-cycle cost analysis
LTPP	Long-Term Pavement Performance
MEPDG	*Mechanistic-Empirical Pavement Design Guide*
M&R	Maintenance and rehabilitation
MTBF	Mean time between failures
NAPCOM	National Pavement Cost Model
NCHRP	National Cooperative Highway Research Program
NCDC	National Climate Data Center
NHS	National Highway System
ODOT	Ohio Department of Transportation
PCC	Portland cement concrete
PCI	Pavement Condition Index
PDF	Probability density function
PH	Proportional hazard
PHT	Pavement health track
PMS	Pavement management system
PSI	Present Serviceability Index

PSR	Present serviceability rating
RSI	Remaining service interval
RSL	Remaining service life
SHA	State highway agency
SI	Serviceability Index
SN	Structural number

EXECUTIVE SUMMARY

The remaining service life (RSL) concept has been around for decades and is well entrenched in the pavement community. It is used at all levels of the pavement management decision process to plan for future field construction events. However, there is no single, clear, widely accepted definition of RSL. Moreover, there is a great deal of uncertainty associated with the definition, especially with the use of the term “life” to represent different points in a pavement’s construction history. In addition, “life” is interpreted differently by stakeholders.

To overcome the RSL shortcomings, this framework introduces terminology that removes the word “life” from the lexicon since it is the basis for confusion. Instead, the new terminology, known as the remaining service interval (RSI) introduces the concept of time remaining until a defined construction event is required. Pavements are comprised of interrelated structural parts that can be maintained, preserved, restored, rehabilitated, or reconstructed to serve the intended transportation needs.

The RSI concept does not provide an alternative to assessing the health of the network or making decisions about where to spend the available funds. It simply provides a clear terminology and a logical process that will create a consistent construction event-based terminology and understanding (i.e., types of construction events and the timing of those events within the concept of life-cycle cost (LCC), risk analyses, and other prioritization approaches based on streams of future construction events and benefits to facility users).

CHAPTER 1. INTRODUCTION

INTRODUCTION

The prediction of future pavement preservation, repair, rehabilitation, and reconstruction requirements is the fundamental basis of engineering design and management of pavement structures. Pavement design methods are based on the provision of a pavement structure predicted to remain in acceptable condition under anticipated traffic loads and environmental conditions for a specified number of years. After construction, planning the timing of maintenance, preservation, resurfacing, rehabilitation, and reconstruction activities that take into account the material and structural as-constructed pavement characteristics become important. Life terminology has been developed and used in various ways to describe the expected period of time it will take for a pavement to reach an unacceptable condition state.

RSL is the time from the present (i.e., today) to when a pavement reaches an unacceptable condition requiring construction intervention. While some make the distinction that remaining life is the time until major rehabilitation and RSL is the time until a service threshold is reached, both types of events require some type of construction treatment to correct.

This report provides a framework to replace current pavement life terminology with one based on more exact construction event terms. The remainder of this chapter discusses pavement business decisions and the role that current RSL terminology serves in these decisions. This is followed by a discussion of issues with current RSL terminology.

PAVEMENT BUSINESS DECISIONS

Many decisions need to be made to effectively provide and manage a pavement network. A common method to classify these decisions into groups with common characteristics is through the notion of hierarchal levels within the business management process. The pavement management business processes impacted by these decisions are most often described as network- and project-level decisions.

The purposes and goals of network-level pavement management are normally related to the budget process.(2) Decisions at this level are made by higher-level management positions within an organization with resource allocation authority.

Network-level decisions have many strata starting at the local level and progressing to the national level. In local municipal agencies, network-level decisions start at the city or regional level depending on size and governmental organization. Decisions on pavement networks managed by State agencies can start at a district level but ultimately are made centrally. Primary results from network-level pavement/asset management decisions are the pavement infrastructure needs and necessary funding to effectively maintain and preserve them. At other network-level strata, decisions are made on which segments of the road network are scheduled for future construction interventions requiring project-level plans to be prepared.

Because of the economics of pavement condition field data collection, data requirements to support network-level business decisions must be more aggregated and contain fewer details as one progresses from local- to national-level network strata.

For pavement assets, decisions at the project level focus on providing the most cost effective, feasible, and original design, maintenance, rehabilitation, or reconstruction strategy possible for a selected section of pavement within the available funds and other constraints.(3) The data needs at the project level are the greatest since they result in engineering plans and specifications on treatment activities to be applied to individual projects.

Alternative contracting mechanisms such as design-build-operate and warranty construction are subsets of the more general project-level business decisions and could be classified as a contract administration level type of business decision. Because the acceptance conditions must be specified in the contract, data support for these project-level contracts have an additional burden of withstanding the test of potential contractual challenges.

ROLE OF RSL IN PAVEMENT BUSINESS DECISIONS

Predicting the remaining life of a pavement is a fundamental aspect of pavement management planning. Knowing or estimating the future condition of pavement segments is the rational basis of all informed pavement infrastructure planning decisions. A goal of modern pavement management systems (PMSs) is to optimize agency resource expenditures while minimizing impacts on facility users and the ecosystem.

Pavement infrastructure budget optimization techniques require predicting the change in pavement condition within a defined set of timeframes. Those techniques then predict what is needed under the following action scenarios:

- The do nothing alternative, where no physical road construction event is needed within the planning horizon since the pavement structure is expected to still be in acceptable condition.
- Applications of routine reactive maintenance to correct spot deficiencies.
- Application of preventive maintenance and preservation activities designed to extend pavement service life without significant pavement structural changes prior to the time when reactive maintenance treatments are required.
- Application of alternative rehabilitation treatments.
- Pavement reconstruction.

Table 1 presents a summary of the role of RSL models in business decisions at different levels of pavement management, contract construction, and pavement operation mechanisms.

Table 1. Role of RSL models in levels and types of pavement management business decisions.

Decision Level	Decision	Pavement RSL Model Role
Project design	Rehabilitation treatment selection	Time until pavement structural and functional limit thresholds are reached or exceeded; service life prediction of candidate treatments
	Overlay thickness design	Service life prediction of candidate overlay design thicknesses
	Non-overlay rehabilitation treatments	Time until pavement structural and functional limit thresholds are reached or exceeded; service life prediction of candidate treatments
	Noise mitigation treatment selection	Prediction of increase in noise as a function of pavement age, surface texture, traffic volumes, and vehicle speed
	Friction mitigation treatment selection	Prediction of changes in friction as a function of predicted change in surface texture characteristics and age
Pavement network planning	Needed pavement maintenance budget	Time until pavement functional limit threshold are reached or exceeded; predicted pavement condition as a function of funding allocation
	Needed pavement rehabilitation budget	Time until pavement structural and functional limit thresholds are reached or exceeded; changes in pavement condition for non-treated projects and rehabilitated projects
	Needed pavement reconstruction budget	Time until pavement structural and functional limit thresholds are reached or exceeded; change in pavement condition for non-treated projects and reconstructed projects
	Budget optimization—allocation of resources to projects	Change in pavement condition for non-treated projects, rehabilitated projects, and reconstructed projects
Contract maintenance management	Contractor award fees/penalties	Structural and functional service life prediction as a function of applied maintenance treatments
Contract design/build/operate	Acceptance by public agency at end of contract; decisions based on contract terms	Time until pavement functional need thresholds are reached or exceeded; predicted maintenance-free life; time until rehabilitation is required; predicted performance of pavement until rehabilitation required
Warranty construction contract	Acceptance by public agency at end of contract; decisions based on contract terms	Time until pavement functional need thresholds are reached or exceeded; predicted maintenance-free life; time until rehabilitation is required; predicted performance of pavement until rehabilitation required

As described in table 1, the central role of RSL models in all of these pavement management business decisions is predicting the change in pavement condition as a function of time, traffic loading, and environment. The basic difference in the RSL models used at the project, network, and contract administration levels are data requirements related to level of technical detail, extent, quality, precision, and accuracy of the model inputs. Project- and contract-level models require the greatest amount of input data to satisfy statistically based inferences. Ideally, models used at the project level are expected to be calibrated to local conditions and use better and more data. As a result, they are perceived to be more accurate than models used at network levels since actual engineering decisions are based on their results. Network-level decisions typically result in an allocation of resources, which must be subsequently programmed down to the project level. Since pavement network condition is only one input in this process, data requirements do not currently justify the intensity of project-level data collection.

When the promise of fully automated pavement data collection technology is finally reached, project- and network-level decisionmaking can converge to use a common set of RSL model inputs. The basis of the decisions made at the network planning level will then converge with information used at the project implementation level. Since simplified models are currently used for network-level planning, the assumptions made during the optimization process on the type of future treatments to apply to each pavement segment may not match the actual pavement treatments designed using detailed project-level data. Until the disparity between assumptions used in network-level budget optimization algorithms are matched to the resulting project-level treatment decisions, true network budget optimization is not assured. While this vision of merging network- and project-level pavement management modeling may be somewhat optimistic at this point in time, efforts to reduce network-level data collection costs while providing more information are continuing to be pursued.

ISSUES WITH CURRENT RSL TERMINOLOGY

While the prediction of time until a corrective or preventative construction treatment should be applied is an established critical component at all levels of pavement management decisions, many issues exist in the current RSL terminology and resulting numerics, which confuse, confound, and complicate proper interpretation, interagency data exchange, and use.

One common RSL definition is the time until the next rehabilitation or reconstruction event. Rehabilitation and reconstruction are two very different events in terms of pavement condition at the time of construction and construction costs. The rule of thumb is that rehabilitation treatments should be applied before a pavement has suffered too much structural damage. Otherwise, the rehabilitated pavement structure will not last very long. Reconstruction treatments are generally warranted after a pavement has reached an advanced degree of deterioration. Typically, during the planning process, an agency decides to apply a rehabilitation treatment to extend the time until reconstruction is required. Attempting to interpret combined RSL estimates from mixed rehabilitation and reconstruction units can cause confusion for decisionmakers.

Another common RSL definition is the time until a condition index threshold limit is reached. This approach shares the same issues as rehabilitation and reconstruction RSL units but also introduces other service and safety condition indices, which further complicate the meaning of RSL. Setting threshold limits for pavement conditions that are not based on human subjective ratings, such as cracking, can be complicated to justify. Moreover, interpretation of a single RSL number gets even more complicated when it is based on multiple condition states. For example, if RSL for roughness is 2 years, RSL for cracking is 5 years, RSL for friction is 7 years, and RSL for rutting is 20 years, expressing that the current pavement RSL equals 2 years can lead to imperfect construction decisions since the construction treatment selected to correct roughness may not necessarily address the more serious cracking issue expected to occur soon after the roughness threshold is reached. Since there are many construction treatments that can be used to correct excessive pavement roughness that can be classified as pavement preservation, this approach adds maintenance-type activities to RSL units.

Another intriguing aspect of RSL based on threshold limits is negative RSL. When a Pavement Condition Index (PCI) limit is reached, from a numerical standpoint, the years it remains in service after this time could be considered a negative service life, which is counterintuitive. One approach is to set negative values to zero, thus not allowing a negative RSL value to be provided by the process. Another approach is to consider negative RSL as overdue needs, in which case, the number of years overdue can be considered as additional information to decisionmakers if they know the basis of the condition in need of attention.

Another approach to RSL is based on agency management rules on the time between applications of corrective pavement construction treatments. For example, a State highway agency (SHA) with a relatively small number of interstate highway lane-miles may decide, based on past performance, to apply a resurfacing, rehabilitation, or reconstruction treatment every 8 years to each construction segment unit on the system to keep their highest level functional class pavements in the best condition. The RSL becomes the difference in time between the construction frequency established and how long it has been since the last treatment was applied. While this approach simplifies the decisionmaking and project selection process, it does not typically result in the most cost effective solution.

One unintentional consequence of using current RSL terminology, which is defined as the time to reconstruction or major rehabilitation, is that it tends to promote worst-first approaches to correcting pavement deficiencies. By expressing pavement condition in terms of RSL, laymen and politicians expect that pavements in the worst condition get treated first. Construction treatments on pavements in the worst condition tend to cost the most. Applying a life extending corrective rehabilitation treatment before the pavement condition gets too bad tends to cost less than reconstruction treatments. Optimum allocation of annual pavement resurfacing, rehabilitation, and reconstruction budgets will be a mixture of pavements with differing remaining lives and not based solely on a worst-first approach.

FRAMEWORK PRESENTED IN THIS REPORT

The framework presented in this report is intended to provide a common definition that may be referred to by anyone attempting to evaluate the remaining life or service life of a pavement structure. Chapters 2 and 3 discuss the updated vocabulary as well as the framework associated with RSL development and construction needs assessment. The remaining chapters cover each step of the process including construction triggers, threshold limits, performance curves, inputs, strategy selection, assessments, and updates. The final chapter summarizes the major findings.

CHAPTER 2. REFOCUS OF PAVEMENT REMAINING LIFE VOCABULARY

REFORMULATING RSL TERMINOLOGY

A primary objective of this report is to provide a definition of pavement remaining life that will promote consistency in the use of the terminology. Many RSL definitions are currently used in the pavement community to describe different events in the construction history of a pavement. Construction-related history best describes the use of RSL models in all levels of the pavement management decision process because the primary purpose of predicting remaining pavement service life (or life within the context of modern pavement management) is to plan for future field construction event(s), whether it be the application of maintenance, preservation, rehabilitation, reconstruction, or other treatments to correct some attribute of the pavement structure. Regardless of the name given to different treatments, these are all construction events that cost the highway agency to provide and impact facility users. Ideally, the definition of RSL should be independent of business decisions.

The major source of uncertainty in the current RSL definition is the use of the term "life" to represent multiple points in the construction history. In the pavement design context, "life" is used to represent the time until the hypothetical pavement structure reaches an unacceptable condition since the pavement designer must make assumptions on the pavement properties. In the pavement management context, after construction of the pavement structure, the as-constructed properties become more important in pavement life expectations than the assumed inputs into the original design process. A pavement structure can be thought of as a system whose components include subgrade treatments, subsurface drainage features, base layers, shoulders, bound structural load bearing layers, and surface layers. As a repairable system, the life of the system is not defined by correctable component failures.

The proposed solution to the problem is to remove the word "life" from the lexicon since it is the basis for confusion. Instead of using RSL or structural life, adopting terminology of time remaining until a defined construction treatment is required to replace the generic ill-defined RSL term. This terminology has the ability to unify the outcome of different approaches to determine needs by focusing on when and what treatments are needed and the service interruption created. Thus, RSL is replaced by RSI.

Moreover, adopting a definition related to construction treatments creates new terminology for treatments related to other factors besides pavement condition. For example, if a construction cycle is defined in terms of time until the next construction event requires lane closures, then capacity improvements, shoulder widening, utility construction, and realignment construction activities can be included in the construction event. In turn, this broadens the application of the definition in the future. In some situations, capacity issues can have more of an effect on the service provided by a pavement structure than the condition of the pavement surface. This shifts the emphasis on the life remaining in a pavement structure to the time remaining until the next planned construction lane closure is required or future type of defined construction treatment is needed.

FUNDAMENTAL PAVEMENT PLANNING ELEMENTS

The fundamental elements required to unify RSL terminology include the following:

1. Development of a high order controlled vocabulary used to define pavement construction events. The objective of this vocabulary is to uniquely define what type of predicted future construction event is need.
2. A common basis for when the future construction event is needed.
3. How future needs are determined to differentiate between different levels of business decisions.
4. The location and extent of the needed treatment.

The logic of this structure is based on separating the definitions of what future construction event is needed from how the need is determined. Although project-level prediction methods require more intensive engineering data than network-level models, they are used for the same purpose in determining similar types of future treatment needs.

Another need for a fundamental RSL model is to incorporate the service interruption concept. Drawing from the concept of a repairable system used outside of the pavement industry, incorporating service interruption into the model and quantifying the effect on user experience is critical. Thus, some form of user experience (i.e., analogous to functional condition percepts) should be a part of a fundamental RSL definition. In addition, there is the need to model performance from an engineering standpoint, and this primarily involves integrating a structural component into the model. Each of these perspectives must be accounted for as part of fundamental pavement planning activities.

CONSTRUCTION EVENT TERMINOLOGY

The proposed replacement for RSL (i.e., remaining structural life) is RSI (i.e., time until a construction treatment is required). This terminology requires three attributes: time when a treatment is needed, type of construction treatment, and reason for the construction treatment.

The time, or the year, when a treatment is needed is specified as this establishes the funding needs by budget planning years. This is meant to replace prediction models based on traffic applications. Traffic application rates used in the modeling process need to be converted to a time basis. Converting traffic application rates to a time basis is a complex process based on consideration of the design lane (which receives the most truck loadings), multilane facilities, damaged lanes (which are the lanes in worst condition), and other local factors that influence pavement damage from vehicle and environmental effects.

Consistent terminology is needed to describe the construction treatments, promote database integration, and increase the level of aggregation at local, district, State, and national levels. The following examples highlight construction event definitions based on the expanded paradigm of common pavement improvements included in many modern PMSs:

- **Crack sealing**: Application of sealants in surface cracks.
- **Joint sealing**: Application of sealants in preformed joints.
- **Surface treatment**: Application of a layer of material of intended uniform thickness less than 0.5 inches (12 mm).
- **Thin overlays**: Application of a material layer of intended uniform thickness greater than 0.5 inches (12 mm) and less than 2 inches (50 mm) and which does not increase the thickness of the bound material layers by more than 25 percent.
- **Thick overlays**: Application of a material layer of intended uniform thickness greater than 2 inches (50 mm) or increases in thickness of bound pavement layers by more than 25 percent.
- **Concrete pavement restoration**: Application of full-/partial-depth joint repairs, slab replacement, dowel bar retrofit, or other restoration treatments.
- **Grinding**: Removal of portions of the surface layer of a pavement without placement of a new material layer.
- **Grooving**: Cutting of grooves in the surface of a pavement without application of a new material layer.
- **Milling**: Removal of bound portions of a pavement that is associated with placement of a new material surface layer.
- **Undersealing**: Injection of cementitious material underneath bound pavement layers.
- **Reconstruction**: Removal and replacement of all bound layers of an existing pavement.
- **Addition of lanes**: Construction of additional lanes to the facility designed to permit greater traffic capacity.
- **Addition of tied shoulders**: Removal and construction of portland cement concrete (PCC) shoulders tied to adjacent PCC pavement structures.
- **Shoulder widening**: Extending the width of the existing shoulder with use of similar materials.

Note that the definitions only attempt to describe what type of construction treatment is being applied to the pavement.

An indication of the reason(s) why a future construction event is predicted is needed to complete the definition since pavement improvements are based on different needs. The following examples highlight controlled terminology that can be used to explain the basis of predicted time to a threshold event:

- Roughness exceeds *y* International Roughness Index (IRI). The *y* value is the generally accepted limiting value for pavement roughness in terms of IRI.
- Cracking exceeds the limit requiring major rehabilitation.
- Cracking exceeds the limit requiring reconstruction.
- Rut depth correction requires major rehabilitation.
- Rut depth correction requires reconstruction.
- Skid resistance reaches the safety limit.
- PCI reaches threshold *x*. For systems based on a PCI-based index, *x* represents the various thresholds between rehabilitation and reconstruction.
- Present serviceability rating (PSR) reaches *x*. For systems still using the PSR/Present Serviceability Index (PSI) concept, *x* is the serviceability value considered by the agency appropriate for the route classification.

Typically, an agency will develop some sort of decision matrix to use as part of its pavement management. This matrix will associate types of pavement deficiencies requiring construction actions with types of construction best suited to correct them. For example, if the roughness exceeds the IRI threshold, then a typical approach would be placing an overlay to correct the roughness.

CHAPTER 3. FUTURE CONSTRUCTION NEEDS ANALYSIS FRAMEWORK

INTRODUCTION

Consistent terminology is necessary to reduce potential confusion over the use of the term RSL. General guidelines on how to formulate future pavement construction needs analysis are provided in this report. The construction needs addressed in this report are associated with correcting pavement surface and structural deficiencies, although many of these concepts could be adapted for construction related to other needs such as capacity and shoulder improvements.

The basic process to determine future pavement construction needs is illustrated in figure 1. Most pavement construction activity planning is based on an annual fiscal time cycle used by the agency. The steps in this figure are cyclical and depend on the time cycle appropriate to the type of pavement asset. The process starts with input data, which are fed into the performance models that predict future changes in the construction trigger models. The outputs from the predictions are used to select the most appropriate construction strategy, which is used to develop construction plans and specifications. The feedback cycle starts with documenting the actual condition observed over time as well as the actual construction activities performed. Monitoring measurements are performed to provide updated inputs for the next planning cycle.

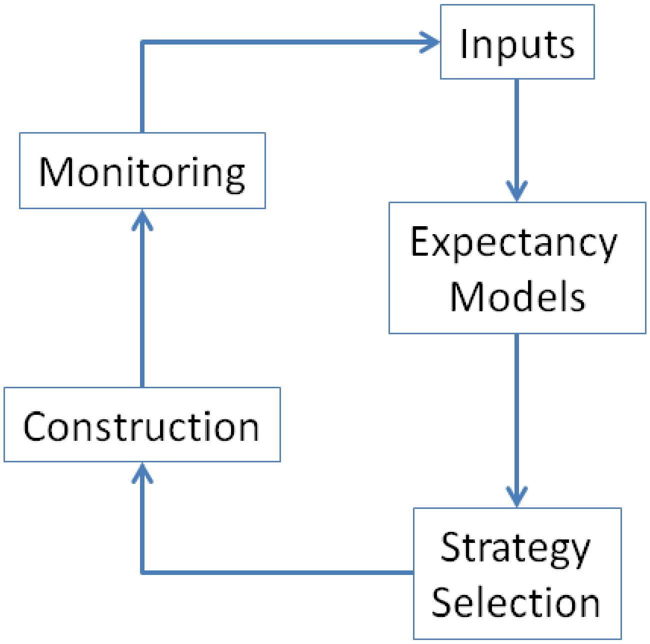

Figure 1. Flowchart. Future pavement construction needs process.

While the basic framework illustrated in figure 1 starts with inputs, the input requirements are based on the model used for construction triggers. The framework discussion starts with construction triggers, which are the basis for setting threshold limits and establishing performance models for factors used to select corrective construction strategies (see chapter 4 for additional information).

The following topics must be addressed to develop, implement, maintain, and update a construction needs analysis methodology:

- Construction triggers.
- Threshold limits.
- Performance curves.
- Collection of inputs.
- Strategy selection.
- Assessment and update.

The methods should be tailored to individual agency requirements related to the budgeting process, types of pavements in use, common types of pavement deficiencies requiring correction, construction contract instruments, and other considerations.

CONSTRUCTION TRIGGERS

A critical step in the construction needs analysis process is to determine the most appropriate pavement factors that should be used to indicate the application of pavement construction treatments. The selected set of construction triggers constitutes the basis for all of the other activities used in the construction needs analysis.

Construction triggers may be distress related (i.e., used to identify specific target levels of cracking, roughness, rutting, or friction) or related to capacity of the roadway (i.e., adding lanes to manage increased traffic levels).

THRESHOLD LIMITS

The next step in the process is to set threshold limits on the pavement factors selected as construction triggers. Crossing a threshold limit can indicate the need for a construction treatment. Pavement condition assessment is complicated with the use of hierarchical threshold limits of construction needs for the same condition factor.

PERFORMANCE CURVES

Because the goal of this activity is to plan for future construction events, some form of performance curve is needed to forecast the changes in each construction trigger since the last condition measurement. Performance curves on the rate of change in pavement condition can never be static due to changes in traffic loadings, climate effects, construction techniques and materials, and technology advancement. Keeping pavement performance curves updated with current technology is an apparent intractable problem since long-term observations are generally required to understand how new technology performs.

COLLECTION OF INPUTS

Ideally, pavement management agencies should only collect data needed to support their decisions. Inputs needed to support future pavement construction needs include the condition of construction triggers, explanatory variables used in performance curves, basis of threshold limits, and construction costs.

STRATEGY SELECTION

The strategy selection process is based on future construction needs when the expected condition state of a construction trigger exceeds a threshold limit. Secondary processes include estimation of construction costs and pavement performance expectation after application of each alternative construction treatment so that cost-benefit-based optimization calculations can be performed.

ASSESSMENT AND UPDATE

All management processes require a formal system that documents current procedures, provides an independent assessment of adequacy and compliance with established procedures, and includes an improvement update process to keep them relevant and technologically current. The formal quality management standards developed by national and international agencies can be used as the basis to develop agency-specific protocols.

CHAPTER 4. CONSTRUCTION TRIGGERS

INTRODUCTION

Construction triggers are measureable aspects of a pavement's condition that can be used to indicate the need for corrective treatment. Selecting construction triggers is the basis for developing field data collection programs to measure the condition state of pavement segments.

Some considerations that should be taken when selecting construction triggers include the following:

- **Historical practice**: This is the starting point for most agencies since time-history pavement condition data are needed to develop and modify performance curves, which are discussed later in this report.

- **Related agency practice**: Piggybacking on practices of related pavement management agencies is a strategy that can be used to potentially reduce field measurement, engineering, development, and software costs. Related pavement agencies are those that are located in the general geographical area, use similar materials, and have commonality in construction practices/pavement contractors. For example, there may be areas of overlap between city, regional, and State transportation authority's managing pavements with common attributes that form a basis for information and technology interchange.

- **Extent of the pavement network being managed**: The greater the number of lane-miles being managed, the greater the need for automation to reduce condition measurement costs. Manual pavement condition measurements performed by crews typically cost more, are slower, and introduce greater safety considerations than automated methods.

- **Data collection budget**: The majority of construction triggers are based on some type of field pavement condition measurement. The type, extent, and frequency of condition measurements are based on the data collection budget and incremental cost-benefit of the data collected relative to the construction decision process.

- **Required measurement accuracy, precision, and detail**: The required accuracy, precision, and detail of pavement condition measurements are related to the use of the information. Project-level measurements, which are used to develop construction plans and specifications or are used for contractual acceptance purposes, require the best available standard of accuracy, precision, and information detail content. Network-level measurements, which are used to provide a coarse filter of the condition of all pavements included in the system, generally require less detailed information content and lower levels of precision.

- **Functional class of pavements in the network**: Functional classification of pavements is primarily based on the route locations, role, volumes, and governmental classification in the pavement transportation system. Location is classified as urban or rural. Role is classified as local, collector, arterial, or interstate. Traffic volume is used to differentiate between minor, major, and principal routes. Generally, as the level of functional class progresses from rural local collector roads to urban principal arterial interstates, pavement structures also change in thickness, strength, materials, and base needed to support the increased loads.

- **Pavement types or pavement families**: A pavement family is a group of pavement structures constructed with similar structural materials, construction methods, pavement components, and experience loading conditions and are expected to have a common set of distress mechanisms.

- **Common distress manifestations**: Patterns found in the common types of distresses experienced in pavements in the managed network can be used to refine the set of construction triggers requiring field data collection. This type of refinement can be based on an analysis of what project-level data are most critical to the selection of corrective construction treatments. A successful strategy is to reduce network-level pavement condition measurements to those that most influence corrective construction within the managed network.

- **FHWA Highway Performance Monitoring System (HPMS) reporting requirements**: SHAs required to submit pavement condition data on HPMS sample sections in their jurisdiction to FHWA can leverage the Federal research and development resources being allocated to update and modernize the national system of pavement infrastructure needs analysis. SHAs can use the findings from these FHWA research and development efforts to improve their pavement construction needs planning processes.

LEVEL OF SERVICE

Level of service construction triggers are primarily based on human factor ratings of the pavement serviceability and pavement roughness measurements.

The use of pavement roughness as a primary indicator of level of service is based on the American Association of State Highway Officials (AASHO) Road Test conducted in the 1950s.(4) Participants provided a PSR on a set of test sections whose attributes were also measured using the best available objective technology at the time. A PSI predictive equation was developed to estimate PSR from the objective ratings. The pavement roughness component accounted for about 85 percent of the variation in the PSR ratings, which verified the expectation that pavement roughness was the primary determinant of pavement level of service from a user standpoint and provided a basis to scale the pavement roughness measurement numerics. Although the AASHO Road Test PSI equation also included statistically significant terms for cracking and patching, the pavement industry has evolved to where pavement roughness, expressed in terms of the IRI, is the most common measure of pavement level of service.

PAVEMENT SURFACE DISTRESS

The type, extent, and severity of pavement surface distresses are the basic elements used to describe pavement distresses. The fundamental classifications of pavement distress are related to fracture, deformation, and disintegration of the pavement material.

While national standards exist for more than 15 possible types of pavement distress attributes for each type of pavement, they are not all typically required for pavement construction decisions. Reducing the number of distresses to a small number of core distresses can reduce field data collection costs. Methods that can be used to create construction triggers based on pavement distress measurements include the following:

- Survey the predominant types of distresses common to an area or region that deteriorate the quickest and require construction intervention to correct. Typically, pavements that are constructed in a jurisdiction using similar materials and that are subjected to the same environment have similar patterns of distress.
- Use the predicted distress types from the pavement design method.
- Create or use an existing numerical index based on assigned deducted values for the type, extent, and severity of a selected range of distresses.
- Develop a correlation between distresses and level of service indicators.
- Associate distress types with corrective treatments. For example, potholes can be corrected with patches, while severe fatigue cracking usually requires pavement reconstruction.

STRUCTURAL CONSIDERATIONS

Pavement structural considerations are based on certain types of distress and non-destructive pavement deflection testing.

The primary distinction of distresses most often associated with structural pavement damage is those whose mechanism of formation is due to the application of wheel loads. Common distresses associated with pavement structural integrity include cracking in the wheel path (fatigue cracking), corner cracks on jointed PCC pavements, faulting on jointed PCC pavements, punch outs on continuously reinforced concrete pavement, and rutting associated with subgrade and base instability. A secondary consideration is distress types that contribute to the acceleration of structural damage.

While surface cracking can be an indicator of pavement structural damage, some pavement preservation treatments hide surface cracks. Deflection measurements can be used as a diagnostic tool to look below the pavement surface to determine subsurface damage.

Pavement deflection measurements can be interpreted to characterize a variety of pavement structural conditions. The basic concept behind deflection measurements is the measurement of the deflection of the pavement surface under the application of a known load. Information can be obtained from devices that measure the deflection basin at various distances from the load center and from devices that apply multiple load levels at the same measurement point. A comparison of the changes in deflection response and associated computed parameters along a pavement can reveal the extent of damage not yet visible.

Pavement structural information from deflection measurements includes the following:

- Computation of the modulus (stiffness) of the pavement foundation layer (subgrade) from a forward calculation.
- Indicators of the relative stiffness of the surface and base layers using deflection basin indices.
- Load transfer across joints and transverse cracks in PCC pavements.
- Stiffness characterization of distinct pavement layers from a backcalculation, which requires layer thickness information. These properties can be used as inputs to a variety of pavement performance prediction models.
- Computation of the effective structural capacity based on the 1993 *American Association of State Highway and Transportation Officials (AASHTO) Guide for Design of Pavement Structures* methodology.(5) Structural capacity is defined as the structural number (SN) for flexible pavements and thickness of the PCC layer for rigid pavements.

SAFETY

Safety aspects of a pavement condition are primarily related to friction and hydroplane potential. Pavement friction characteristics are most often characterized using a skid number parameter. These parameters are based on field measurements using locked wheel, limited slip, or yaw mode friction testers. Hydroplane potential is related to the ability of pavement ruts to hold water. The nominal depth of water retained in the ruts can be associated with hydroplane potential based on the speed limit.

Another safety concern is excessive pavement roughness relative to the speed limit. It is possible for localized bumps, dips, faults, and holes in the pavements to negatively influence vehicle control.

AGENCY TIME-BASED RULES

One of the simplest construction needs triggers is the time since the last construction treatment. Some agencies have implemented rules on the maximum amount of time between construction events. Time-based rules are intended to reduce field measurement costs and provide a proactive pavement management approach to keep pavements in good condition.

TRAFFIC CAPACITY

In changing the definition of RSL to one that is related to assessing future construction needs, it is important to identify when roadways need to be expanded by adding new lanes due to traffic growth. These types of rules are generally outside the realm of pavement management, but they should be considered when developing an estimate of future budget needs.

CHAPTER 5. THRESHOLD LIMITS

INTRODUCTION

Threshold limits are used to indicate when a construction trigger reaches a condition when a corrective or preventative construction treatment is needed. This chapter presents various methods and procedures that can be used to establish threshold limits.

In this discussion, maintenance and preservation maintenance treatments do not include routine and catastrophic maintenance. The activities included in this category are planned projects that include pavements longer than 4 mi (6.4 km) that are designed to extend the time until rehabilitation and reconstruction treatments are required. Since the distinction between maintenance, preservation maintenance, and rehabilitation treatments is often dependent on funding sources, the definitions used by the funding sources for allowable treatments should be incorporated into the development of threshold limits.

Rehabilitation treatments include extensive restoration treatments and structural overlays. The general definition of *structural overlays* is the addition of a new material layer whose thickness is greater than 15–25 percent of the existing bound pavement layers.

A common definition of *pavement reconstruction* is the removal and replacement of all existing bound pavement layers. This definition includes situations where removal and replacement of the unbound base and subbase layers are also required in addition to the bound surface layers.

SUBJECTIVE THRESHOLD LIMITS

Subjective threshold limits are based on ratings determined by panels of judges that include laymen facility users, pavement experts, or a combination. Generally, a formal rating scale is created and used by the judges, and statistical methods are then used to interpret the ratings and establish limits.

Subjective ratings can be used to define an absolute acceptable limit or degrees of acceptability for a measured condition attribute. The following acceptance scales can be used to capture subjective panel ratings:

- **A binary or two-level acceptable/not acceptable or pass/fail rating scale**: While this type of forced choice acceptance scale purposefully limits the range of response to identify the acceptance threshold, it also limits analysis of the results.
- **A five-level Likert scale**: This type of scale provides a measure of the range in acceptance criteria to be considered. An example rating scale for the condition of a pavement test section is as follows:
    - 5 = Totally acceptable.
    - 4 = Slightly acceptable.

    - 3 = Neutral or not sure.
    - 2 = Unacceptable.
    - 1 = Totally unacceptable.

  A key feature of this type of rating scale is that it allows greater options in the analysis of the ratings. The neutral center point value is a measure of the gray area between acceptance and non-acceptance. The ratings can be converted to a three-level scale by combing the two acceptable ratings and two unacceptable ratings.

- **A four-level Likert scale**: The purpose of the four-level scale is to remove the neutral middle rating to force raters to provide either an acceptable or unacceptable rating. In some cases, trying to interpret the meaning of neutral ratings can be confounded with factors not related to the pavement condition of interest. An example of a four-level scale is as follows:
    - 4 = Totally acceptable.
    - 3 = Slightly acceptable.
    - 2 = Unacceptable.
    - 1 = Totally unacceptable.
- The degree of acceptability can also be based on a Likert scale by altering definitions of the ratings as follows:
    - 5 = Very poor.
    - 4 = Poor.
    - 3 = Fair.
    - 2 = Good.
    - 1 = Excellent.

In this example, to improve the repeatability of the results, it is useful to provide the raters with a more refined definition of each category that is related to the attribute of interest. The cardinal ordering of the scale can also have an impact on the scoring. In this example, the largest value is assigned as the worst condition state, although most grading scales use the largest value to represent the best condition state.

Subjective ratings can be influenced by a wide range of factors, some of which may not be desired or can overly influence the ratings. For example, road roughness is commonly expressed using the IRI parameter computed from measured longitudinal road profiles. A method to determine levels of acceptability to riders is to have a panel rate the acceptability of a set of test sections with a range of roughness by driving over them. In this case, the following factors can influence the ratings provided by the panel:

- **Suspension characteristics of the vehicle used by the rating panel**: People riding in vehicles with soft suspensions will feel less vibration than those riding in stiff suspension vehicles.
- **Vehicle speed**: The suspension response of a vehicle is greatly influenced by vehicle speed. Since IRI is standardized to a constant speed, test sections with the same IRI can have different degrees of acceptance depending on how fast the vehicle is travelling.
- **Distress condition or appearance of the test section**: While the purpose of the rating is to judge the level of pavement roughness, it is known (from the AASHO Road Test and other studies) that raters can be influenced by other factors such as the amount of cracking and visual appearance of the test section surface.(4,6)
- **Climate conditions during rating sessions**: High winds can cause movements in the measurement vehicle that are not due to the roughness of the pavement.
- **Quietness of the test vehicle**: The noises heard while driving can be more related to the texture characteristics of the pavement surface than the pavement roughness.
- **Type of pavement**: The roughness producing characteristics of a jointed PCC pavement are different than those of an asphalt concrete (AC) pavement.
- **Alignment of the pavement test section**s: Horizontal curves, cross slope changes, and vertical grades can influence the response of the rating vehicle.
- **Driver of the rating vehicle**: The method the driver uses to maintain speed can influence the response of the rating vehicle.

A field experiment should be developed to attempt to control or measure the statistical significance of cofactors that can influence subjective ratings.

ENGINEERING CONSIDERATIONS

Engineering considerations used to establish threshold limits are based on pavement performance mechanistic concepts or pavement-vehicle interaction factors. Examples of engineering considerations include the following:

- It can be postulated that when cracks extend completely through the bound layers of a pavement, they allow entry of surface water into the unbound layers. Accumulation of water in the unbound layers can advance the rate of pavement deterioration and cause damage that is expensive to repair. Applying a corrective treatment before the cracks reach this state can help preserve the integrity of the foundation support and extend the time until rehabilitation or reconstruction is needed.

- Research has shown that hydroplaning potential of a vehicle is related to the depth of water and vehicle speed. It is possible to establish a threshold water depth for the design vehicle speed of a route. Assessing the potential water holding capacity of a rut requires consideration of more than rut depth. Factors such as shape of the rut, rut location, and pavement cross slope can be determined from the modern generation of high-speed road condition survey devices that measure the pavement's transverse profile. Computer programs can determine the actual water depth potential from these types of field measurements.

- The perpetual pavement concept developed for AC pavements is based on the premise that an adequately thick asphalt pavement placed on a stable foundation will resist distresses that form at the bottom of a pavement structure and are costly to correct. By limiting distress formation to the pavement surface layer, the pavement life can be extended in perpetuity by rejuvenating the pavement surface materials in a remove and replace type of maintenance operation. The prime consideration in this type of pavement system is to plan future construction events to limit the depth of the top-down cracks. However, measuring the depth of top-down cracks from project-level field measurements is a challenge.

- As pavement roughness increases, the level of dynamic load impacts on the pavement structure from heavy trucks also increases. Since mechanistic principles of pavement performance are primarily based on the magnitude and frequency of applied truck loads, in theory a limit on pavement roughness should exist where the magnitude of the applied dynamic loads accelerate the structural damage to the pavement. The algorithm created to assess the adequacy of pavement smoothness for location of weigh-in-motion scales is based on computation of the increase in the level of dynamic truck wheel loads from the same field data used to compute IRI.

- Pavement structural capacity diminishes to the point where stress and strain levels of applied traffic loads accelerate pavement damage. The results of non-destructive pavement deflection testing can be used to assess changes in pavement structural properties related to resulting increases in stress/strain responses in critical pavement structural layers.

EMPIRICAL METHODS

Empirical methods are based on observations of events. The historical context of empirical methods is based on the scientific process where findings are based on experimental observations. Within the current pavement engineering nomenclature, the empirical part of the *Mechanistic-Empirical Pavement Design Guide* (MEPDG) was calibrating the mechanistic prediction models to field performance observations.(7) Thus, establishing threshold limits using an empirical approach is based on observations of past events, which may or may not be based on mechanistic engineering principles.

A critical aspect of empirical models is that they are most applicable to the inference space of the observations from which they were developed. Technology advancements or other changes that are outside of the inference space of the original observations can limit the applicability of existing empirical models to future events.

Examples of empirical approaches used to set threshold limits include the following:

- Analysis of friction data and associated accidents rates or field experiment to set a safe level of friction.
- Statistical analysis of the pavement condition when construction treatments have been applied.

The advantage of this type of analysis is that it does not require a thorough understanding of the mechanism being modeled. For example, one can postulate that the accident rate on a section of roadway is related to the level of friction offered by the pavement surface. One may also recognize that the accident rate on this same section of roadway is related to the speed of the vehicles traveling on that roadway. With an empirical approach, it is not necessary to fully understand all of the mechanisms associated with the accident rate, which may include psychological factors associated with the drivers. Rather, the correlation of the friction with the accident rate can assist in identifying an unacceptable level of friction on the roadway.

ECONOMIC ANALYSIS

Construction limit thresholds can be developed from an economic analysis of construction time-series costs over a long-term period. This analysis depends on knowing or estimating how long alternative construction treatments will last based on the predicted condition of the pavement at the time of the treatment and the cost of the construction treatment. By running Monte Carlo simulations with alternative construction treatments performed at different times, a minimum worth cost can be found as a function of pavement condition. The length of the analysis time period has to be long enough so that the pavement deterioration condition factors eventually force a needed construction treatment.

Figure 2 illustrates the expected outcome of an economic analysis on the most cost effective repair strategies as a function of pavement condition for an individual pavement. Plateaus in repair costs will exist since the same construction treatment will correct a range of pavement distresses and severities. A common construction treatment can be specified for a length of roadway based on the worst condition in that segment. The upper plateau represents the cost to reconstruct the pavement after it has reached a condition state where maintenance and rehabilitation (M&R) treatments do not last long enough to be cost effective. Likewise, the rehabilitation plateau represents a common set of treatments that do not require complete removal and replacement of all bound pavement layers. The significant concept illustrated in this figure is that breakpoints should exist in the pavement condition-repair cost relationship that is expected to be unique between different pavements types, load magnitudes, environmental conditions, agency repair policies, and construction costs.

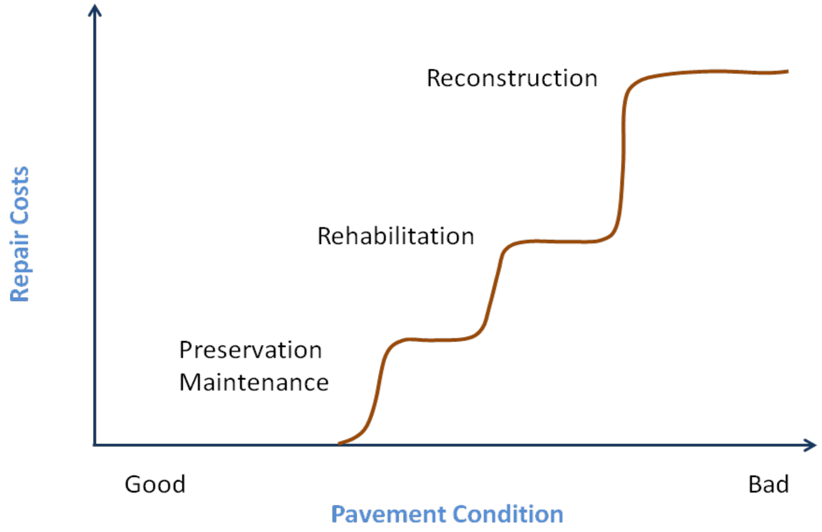

Figure 2. Graph. Conceptual relationship between agency repair costs as a function of pavement condition.

Critical factors in pavement construction time-series economic analysis include the deterioration rate of the pavement, what type of repair treatments are considered, the effect that pavement condition has on the resulting performance for each repair treatment, and costs included in the analysis. To avoid manipulation of the results from pavement life-cycle cost analysis (LCCA) due to the assumptions of the person performing the analysis, SHAs need to create a set of rules to be used in this type of analysis. To the extent possible, the rules should be based on observations from pavements under agency jurisdiction. However, repeated findings from research studies on this topic indicate that not enough field data exists to create these models with certainty. As a result, agencies may need to use engineering judgment based on available data to create the rules. Establishment of a preliminary set of rules provides a basis to evaluate and update the rule set based on experience. Part of the rules should be standard estimates of error and error distributions forms for use in stochastic/risk-based analysis.

COMBINATION OF APPROACHES

The development of successful threshold limits may best be accomplished through a combination of the approaches previously described. Pavements are complex structures designed to serve a vast array of vehicles operated by users with differing requirements. Development of threshold limits on various measures of pavement condition to indicate the need for a corrective construction treatment must also take into consideration management agency policies, agency managed infrastructure asset-to-budget ratio, multiple funding sources, and user expectations relative to the role of the route in the local transportation system.

The recommended approach to setting threshold limits on need for corrective construction intervention is by use of a combined engineering economic approach. The objective should be to determine condition states where maintenance or preservation treatments, rehabilitation treatments, and reconstructive treatments are most cost effective.

Considerations to determine appropriate pavement state thresholds for application of maintenance or preservation treatments include the following:

- Conventional practice is that preservation or preventive maintenance treatments should be applied while a pavement is still in relatively good condition. In theory, pavements still in excellent condition with no defects should not require treatments. The issue becomes determining when treatments are best applied. When possible, the upper limit should be based on specific pavement defects which can be corrected to a good-as-new condition without the need for structural restoration treatments. If aggregated distress-based indices are being used, then use of expert subjective opinions can be used to determine a nominal threshold value when preservation maintenance activities can be used.

- One strategy for setting threshold limits for pavement condition to determine when preservation treatments are applicable is by considering when the extent and severity of distress types have reached levels requiring corrective treatments for structural improvements and preservations treatments are no longer adequate. There is a point when the extent of the required treatment represents a structural improvement or crosses the capital improvement cost threshold. Some examples include the following:

    - The number of locations per mile requiring full-depth repair exceeds 10–30 percent of the surface area depending on the pavement and distress type.

    - Extent of faulting of jointed PCC pavement requires the combination of grinding, ultra-thin overlays, and dowel bar retro fit to correct.

    - The severity and extent of alligator or fatigue-related cracking in the wheel paths requires full-depth patches on more than 10 percent of the section length.

    - When structural and restoration treatments cost less than alternative spot repairs.

    - When pavement roughness reaches a level that causes a significant increase in vehicle operating costs.

One rule of thumb is that an overlay thicker than 2 inches (50 mm) is considered a structural improvement regardless of the depth of material milled from the pavement surface. Another common threshold rule used is that when the treatment cost rises to a certain level set by the agency, it is considered a capital improvement project and requires formal engineering plans and specifications. Like definitions of preservation maintenance, the definition of pavement rehabilitation is also dependent on available funding agency sources. The upper pavement condition threshold limit for rehabilitation is based on when preservation maintenance is no longer effective. Lower limit rehabilitation pavement condition thresholds are based on when reconstruction becomes the most cost effective treatment.

There are also situations when structural defects may require reconstruction to correct even though all other functional aspects of the pavement are acceptable.

CHAPTER 6. PERFORMANCE CURVES

INTRODUCTION

Performance curves are used as a means to predict the time when a pavement's condition will reach a construction trigger threshold. While the results of current pavement condition states can be used to respond to conditions, long-term planning of future needs and optimization requires the prediction of future pavement changes.

A key consideration in the development of performance curves is grouping pavement types into categories of pavement families. A pavement family is a group of pavement structures constructed with similar structural materials, construction methods, pavement components, and experience loading conditions and are expected to have a common set of distress mechanisms. The number of pavement families that should be used depends on the diversity in types of pavement structures with an agency's jurisdiction and the amount of time history data available for each defined family of pavements.

The best practice is to base performance curves on the analysis of pavement performance history observations. This requires the availability of uniform long-term time-series data on pavement condition that are linked to measured pavement features that permits application of mechanistic-based performance models. When empirical data are not available to formulate proper statistical models of future performance, expected performance curves based on the best available information can be used as a surrogate starting point to judge the relative performance of pavements. For example, the knowledge of engineers with long-term experience in a region can be used as a surrogate starting point. While the use of expert subject opinion can be used as a starting point for creating performance curves, the curves should be updated over time with field measurements to improve their accuracy and applicability.

MODELS BASED ON DESIGN EQUATIONS

Performance curves used for pavement design can be different than those used for pavement management. The performance curves used for pavement management can be based on empirical survivor statistics, which lack explanatory terms for differences in factors considered during pavement design. Pavement design performance curves require models that provide a measure of predicted future performance as a function of controllable design factors based on uncontrollable design requirements. Controllable design factors include man-made aspects of pavement structures, while uncontrollable design requirements include changes in climate, future traffic loads, and earthquake events. While pavement performance curves used for pavement design can be used for pavement management, pavement performance curves developed from pavement management data may not be appropriate for pavement design use since they may not be sensitive to controlled pavement design factors. A simple example is that a statistical analysis of time until pavement reconstruction is not sensitive to pavement thickness because all of the pavements included in the analysis had approximately the same thickness.

Models based on the 1972 *AAHSTO Interim Guide for Design of Pavement Structures* equations and subsequent updates have been used by some agencies.(8) Pavement condition is expressed in terms of PSR or PSI, and pavement structure capacity as SN for flexible pavements and slab thickness for PCC pavements. Using this system, resurfacing or reconstruction is indicated by the level of PSR. When the predicted pavement PSR in an analysis cycle drops below a minimum tolerable condition based on highway functional classification, then resurfacing was indicated. Reconstruction was triggered if the PSR dropped below the lower reconstruction threshold if the section was not previously selected for resurfacing.

While the legacy AASHTO pavement design equations served the industry well by providing a basis for the design of the interstate system and other pavements in the United States, their use in pavement management has some limitations. Because PSR/PSI is used as a measure of pavement condition, it is not a good measure of what future construction treatments are required since it is most sensitive to pavement roughness. Updates to the 1972 *AAHSTO Interim Guide for Design of Pavement Structures* equations were made over the years by adding more terms to allow greater calibration to local conditions.(8) These updates did not change the fundamental nature of using PSR/PSI as the primary measure of pavement condition.

FHWA has developed a set of performance curves based on the MEPDG for use in the Highway Economic Requirements System (HERS), National Pavement Cost Model (NAPCOM), and pavement health track (PHT) analysis tools.(7) Simplified models based on the use of the default level 3 MEPDG inputs along with the HPMS data are used to predict changes in the multiple pavement condition measures adjusted for current and past observed levels. The following distress prediction models are included in the tool:

- New hot mix asphalt (HMA) and HMA overlay of existing HMA.
  - Alligator cracking.
  - Rutting.
  - Transverse cracking.
  - Smoothness—IRI.
- New jointed plain concrete pavement (JPCP).
  - Transverse cracking.
  - Transverse joint faulting.
  - Smoothness—IRI.
- Composite—HMA overlay of existing PCC.
  - Reflection cracking.
  - Smoothness—IRI.

The use of specific types of pavement distresses as construction triggers at the network level allows for greater flexibility in assigning and determining the cost of future construction needs. This permits the application of automated rational decision tree logic to the selection of appropriate treatments based on multiple aspects of pavement condition.

The use of complex pavement performance prediction models, such as those used in the adaptation of the complex MEPDG pavement design models, is an example of how detailed research findings can be adapted to the management of pavement assets. The key to implementing these complex models, which are based on hourly changes in climate, traffic, and material properties, is to simplify them to the level commensurate with the intensity of data collection and sensitivity of business decisions.

EMPIRICAL MODELS

Empirical models are based on observations of events. All pavement mechanistic models based on the theoretical response of pavement structures to wheel loads and environmental factors need to be adjusted to fit field observations. The numbers of factors that have the potential to influence the performance of a pavement are greater than can be explained by available mechanistic models. While advancements are being made in pavement measurement technology, there will always be the need in pavement engineering practice to calibrate theoretical considerations to field observations.

The following list summarizes empirical approaches used to model pavement performance:

- **Survivor curves:** The various approaches used to develop survivor curves based on life table, Kaplan-Meier, or failure time theory approaches (see appendix B of this report) are based on the prevailing definition of pavement death as defined by each agency. These legacy survivor curves have been replaced with more modern engineering change of state models, which can be used to estimate future construction needs not properly reflected by the variability in past definitions of pavement death.

- **Failure Cox Proportional Hazard (PH) model**: This statistical model form is recommended as the basis for future developments in empirical performance curves for pavement management applications (see appendix B). The statistical approach appears suited to pavement performance management data. The Ohio Department of Transportation (ODOT) has used this approach to create a prediction model based on their pavement condition rating scale.

- **Numerical regression models**: Numerical regression models are used to find the best numerical functional form that describes the variation in the relationship between variables being compared. Regression models only describe the numerical relationship in the available observation data and are most applicable to that inference space. Extrapolation beyond the inference space should include an estimate of the magnitude of variability in the prediction.

- **Bayesian statistical updates**: Updating prior models with new data can be based on Bayesian statistical concepts. A key component in Bayesian statistics is the weight given between prior and posterior observations.

- **Neural network models**: Neural networks are models inspired by the way biological nervous systems, such as the brain, process information that have the capability to fit the variations in observed data that is not possible by using traditional numerical regression techniques. Research to extract information from neural analysis similar to that inferred by numerical regression-based model forms is being pursued.

Some measure of variability distribution for the function and its relevant factors should be contained in all predictions of future pavement condition states. These measures can be used to accumulate future risk probabilities in the prediction based on the variability in the input parameters and prediction models. The FHWA LCC models are an excellent example of how variability can be propagated into the final decision tool.

AGENCY TIME-BASED RULES

The simplest performance curve is a time-based rule for future construction treatment. This type of rule does not require investment in field measurement devices and custom computer programs to predict future events. However, this approach does not provide a basis for optimization of utilization of constrained agency resources.

An example of a time-based rule is that an agency decides that some type of corrective construction treatment will be applied on its rural interstates every 8 years. The network is segmented into contiguous projects, and a construction rotation sequence is established. An appropriate correction strategy is selected and applied during the target construction year. Thus, the performance curve for the time until the next construction event is the time remaining until the next target construction year.

CHAPTER 7. COLLECTION OF INPUTS

INTRODUCTION

Collection of data on the condition state of pavements under an agency's jurisdiction should be based on the same construction triggers that form the basis for local decisions on corrective construction needs.

Field data collection on present pavement conditions should properly be used to determine the impact of the data element on future construction requirements based on the current agencies construction triggers. This effort is complicated with the need to adapt past and new pavement condition measurement practices.

The current challenge to SHAs is integrating, adapting, and adopting advancements in measurement of the physical features of pavement assets to legacy management systems. The development of datasets to establish performance curves of the long-term performance of a pavement requires a uniform set of data based on uniform measurements. Since common past pavement design practice was based on a 20-year life span, developing datasets with consistent data over this type of timeframe is difficult at best. This challenge will continue since emerging practice is to design pavements with even longer life spans (i.e., 50 years).

PAVEMENT ROUGHNESS

The use of high-speed longitudinal pavement profile equipment has become an accepted industry standard used to measure pavement roughness. The technique uses an inertial profiler that measures the change in longitudinal profile in the wheel paths at or near the speed limit. Roughness indices are computed from this profile and summarized at user-defined intervals. IRI is one of the most commonly computed pavement roughness measures. Other pavement condition feature measures and indices can be computed from this type of profile data such as the roughness index, half-car roughness index, ride quality index, ride number, profilograph index, rolling straight edge simulation, "bump/dip" detection, fault heights on jointed PCC pavements, slab curvature on jointed PCC pavements, heavy truck dynamic loading index, etc.

If pavement roughness measurements are performed using inertial longitudinal profiler devices, both network- and project-level data requirements can be satisfied using this common set of data.

PAVEMENT DISTRESS

Pavement distress ratings can be performed by human raters driving the pavement network using a manual process, a semi-automated process where field collected images are interpreted by human raters in an office, or fully automated systems. Manual pavement distress measurements that require raters to drive each route typically cost the most, put raters at risk (raters must drive and get down on the road to note any necessary information), and generally have the greatest variability in the ratings. In the semi-automated process, pavement distress ratings are performed using field video images, which reduces the risk to the raters and provides a historical archive of images for use in project-level investigations. Fully automated pavement distress ratings systems uses computer algorithms to interpret distresses obtained from field images and/or three-dimensional measurements. It offers the potential to reduce the cost of collecting data by eliminating the need for human interpretation. The newer three-dimensional imaging technology, which assigns a depth to image pixels, provides a more robust dataset that can be used for pavement cracking, rutting, and possibly pavement roughness measurements.

PAVEMENT STRUCTURAL RESPONSE

Deflection measurements are used to measure the response of a pavement structure to a known applied load. Interpretation of the resulting deflection data ranges from the identification of weak spots to advanced non-linear characterization of the engineering properties of pavement material layers.

Pavement deflection measurement techniques vary by the types of applied load, load magnitude, deflection measurement characteristics, and traffic control requirements. The types of applied loads range between nearly static creep, sinusoidal dynamic loads, impact loads, and wheel loads. Many modern deflection measurement devices allow the application of different applied load magnitudes that approach the legal limit of truck axle loads. Devices that measure the resulting deflection basin as a function of distance from the applied load allow the application of engineering algorithms to characterize the material properties of pavement layers. Pavement deflection measurement devices currently used in practice must stop at each measurement location, which requires traffic control.

FHWA has supported the development of a rolling wheel deflection measurement device that does not require traffic control. While this device can measure the maximum deflection response under the moving wheel load, it is not yet capable of measuring the shape of the deflection basin around the moving wheel load. While some maximum deflection pavement performance models exist based on the old Benkelman beam measurement technology, the shape of the deflection basin is currently required for pavement deflection analysis tools.

To ensure accuracy of data interpretation using pavement deflection response devices, it is important to know the pavement thickness and types of near-surface material layers. Manual measurement techniques of pavement thickness are being replaced by automated ground penetrating radar technology. Network-level pavement deflection measurements and estimation of pavement structural condition from those measurements can aid in identifying more cost effective future construction actions by incorporating structural information in addition to surface distresses in to the decisionmaking process. The cost associated with the network-level deflection measurements can be justified by the overall economic benefit obtained from optimum decisions that consider structural condition in addition to surface conditions.

In most situations, pavement deflection measurements are performed at the project level as a basis to develop design specifications for the most appropriate construction treatment.

TRAFFIC LOADS

Pavement structures are designed to endure heavy truck loads. Since pavement damage has been shown to follow a fourth power exponential relationship to the magnitude of wheel/axle load, some measure of the upper 20 percent of applied heavy axle loads can account for up to 80 percent of the predicted damage potential of those loads. The truck load damage exponent can also be as low as 2.5 depending on the distress type. It is also possible that one truck overload can destroy a pavement structure in one pass. This is why most highway agencies have imposed truck axle load restrictions and use full-time load measurement scales to enforce regulations.

In order to accurately predict future pavement performance, engineers need to know actual heavy loads being applied to a pavement. Access to permitted overloads granted by other divisions within an SHA is important in determining the need for future construction intervention events.

At the network level, research has shown that measuring the type of trucks on a route is more important than the weight of the trucks. This is based on the observation that truck weights are determined by the type of truck. Within a localized region, a typical heavy load truck profile can be applied to trucks in the same classification with an acceptable level of uncertainty.

CLIMATE

Climate data are at best a second-order consideration in the planning of future construction needs. These data measure potential climate-related “loads” such as freeze-thaw cycles and temperature-induced stresses that a pavement may need to resist based on material properties (as affected by climate) and constructed drainage features. Predicting future climate change and accounting for it is not currently incorporated in most pavement management models.

The best source of historical raw climate data in the United States is available from the National Climate Data Center (NCDC). In the past, NCDC data users needed to conduct quality data checks on the NCDC data to avoid using erroneous data; however, NCDC now provides data that have been subjected to quality checks.

MISSING DATA

All infrastructure management systems require a mechanism to handle missing measurement data. One approach is based on the truth-in-data concept in which all data are labeled as observed or imputed. Imputation of missing data based on defined and documented methods is acceptable, provided imputed quantities are appropriately identified.

The best practice is to associate a measure of variability with both measured and imputed condition state parameters. It is expected that the variability of imputed parameters will be greater than those based on measurements.

MEASUREMENT VARIABILITY

A requirement for all input measurement methods is to provide a measure of variability related to their use in prediction models. These measures of variability should be propagated through the models used to predict future pavement condition states to create a posterior probabilistic-based performance curve of future condition state. Variability measures should include repeatability of the measurement method, be partitioned by spatial variation in the pavement response, and reflect the sensitivity of the prediction model to resulting damage estimates.

SAMPLING INTERVALS AND FREQUENCY

Collecting pavement condition data on a partial sample of a network is used to reduce data collection costs. While sensor data such as pavement roughness and rutting are collected continuously, distress data are most often obtained on a sample basis. For manual condition surveys, field crews travel between selected portions of the roadway on which the distress surveys are performed. For semi-automated distress surveys where interpretations of distress are made from video images, only a portion of the video image can be interpreted on a sample basis. The condition ratings from these samples are then used to represent the condition of a larger pavement segment. Findings from recent research on the effect of pavement sampling on errors compared to a continuous measurement include the following:

- For a distress data sample size of 10 percent, errors have been found to have a typical maximum of 400 percent as compared to continuous data. An example of a 10 percent sample size would be rating 0.0621 lane-mi (0.1 lane-km) for every lane-mi (lane-km) of road.
- A 60 percent sample size reduces the error to approximately ±25 percent.(9)
- The error due to sample size increases for pavements with higher variability.

Most agencies use monitoring frequencies of 1, 2, or 3 years between pavement condition measurements. For cracking, 1-year frequencies appear to be the best so that the first appearance of cracking can be detected in order to fit an appropriate model for cracking prediction. Longer intervals for crack monitoring may cause an overestimation of agency costs for pavement repair at the network level. Monitoring IRI using automated sensor readings could be on a 1- to 2-year interval, although longer intervals will result in an underestimation of repair costs at the network level.(9)

CHAPTER 8. STRATEGY SELECTION

INTRODUCTION

In order to select the most appropriate corrective pavement construction strategies, many considerations must be taken into account, beginning with the pavement condition subject to other constraints such as budget, bridge height clearance, guard rail adjustment, buried utilities, etc. At the network level, the objective is to characterize the current and future condition state of pavements included in the system that require corrective treatments. At the project level, the objective is to provide detailed decisions on what corrective construction treatments are needed for each project identified from the network-level analysis.

The current challenge to SHAs is to create a rational basis to move from a worst-first to a best-first allocation of available agency repair resources. Research has shown that application of corrective construction treatments at the proper time can extend the time until more costly treatments are required. These types of treatments are applied before too much damage has accumulated; hence, the pavements are not in the worst condition. To find these favorable pavement conditions at the optimum time requires knowledge of how a pavement will respond to the prescribed treatment plan based on its current condition.

There are also situations within a pavement network where pavements in a worse condition state should be allowed to continue to deteriorate. This decision is appropriate for pavements that have accumulated significant structural damage but are still smooth and provide adequate service otherwise.

NETWORK ANALYSIS

At the network level, the objective is to characterize the current condition state of pavements included in the system that require corrective treatments. Since network-level data tend to be more aggregated and less specific, the performance models used to predict performance can have greater variability. Likewise, strategy selection may be broken down into broad categories using a standard set of cost assumptions based on the treatment type.

Recommended practice at the network level is to use LCC concepts as a means to optimize the selection of construction projects in the next cycle and forecast future construction needs. These concepts are based on considering multiple streams of future construction activities driven by the prediction of future changes in pavements. Optimization is an objective function whose performance is based on measured field conditions and main factors that are sensitive to future construction activities. In a simple system, optimization is achieved when the best performance of the system is obtained using the available budget.

The pavement performance concept considers the time-history of a chosen functional aspect of a pavement. Serviceability has been used in the past where scale is used—the lower the number, the worse the pavement condition. Using this type of scale, the objective function could maximize the area under of the serviceability-time history curve. If a numeric such as IRI is used, then optimization of the objective function should focus on minimizing the area under the

IRI-time curve since IRI uses an increasing scale where higher numbers indicate pavements in worse condition.

The limitations of construction strategy selection at the network level are determined by the sophistication of the system processes. It is not uncommon that the construction cost assumptions used in the network optimization planning process do not match those developed from project-level design considerations. Continual improvements are being made to field data collection techniques, construction cost models, and new performance prediction curves. Modern automated field data collection systems are capable of providing greater amounts of data with increased specificity that approaches what used to be considered project-level data. This increased data availability requires updates to the construction triggers, threshold limits, and performance curves used by SHAs in their network-level strategy selection process.

Strategy selection at the network level are primarily determined by computer algorithms capable of accounting for all of the factors included in the simulation of future pavement condition states and performing the millions of calculations for impact of alternative strategy scenarios needed for optimization of available budgets.

PROJECT ANALYSIS

Project-level analysis is based on indepth considerations of pavement conditions after a network-level planning process has identified a pavement segment in need of corrective construction. The first level consideration determines the construction need as well as maintenance, restoration, resurfacing, rehabilitation, or reconstruction needs. The most significant difference between network- and project-level strategy selection is that project-level decisions are based on human interpretations of available data and information as opposed to reliance on automated computer algorithms.

At the project level, LCCA can be supplemented with cost engineering considerations specific to each project site. Cost engineering concepts require more intensive inputs on the resulting affects of alternative design considerations than those generally available at the network level. This level of consideration is based on a cost-benefit analysis of alternative construction treatments centered on a greater range of treatment options.

Project construction programming is the last chance to integrate other related infrastructure construction needs into managing pavement assets. In urban areas, the timing of new utility cuts into a pavement structure should be coordinated with repaving events. Having a utility company perform changes to a pavement structure less than 3 years since the last construction event is often an indication of lack of coordination between publically funded city/regional departments. Studies on the impact of the repair of utility cuts in pavements have shown that they return the pavement to less than as new condition and can advance deterioration of the surrounding pavement structure.(10)

CHAPTER 9. ASSESSMENT AND UPDATE

INTRODUCTION

Modern quality management system concepts are based on a continual cycle of assessments and updates. All systems require formal assessments. Based on the results of the assessments, updates are performed.

ASSESSMENTS

Regardless of the age of a management system, formal assessments should be performed at periodic intervals to identify improvement opportunities.

Assessment tactics may include using panels composed of available internal agency staff and external peer review experts. While internal review panels provide recommendations based on the current system, external peer reviews can provide lessons learned from the experience gained from other management methods.

UPDATES

As new materials and construction methods are implemented, the models used for both planning and design need to be updated based on field observations.

Creating a proper database designed to document past construction needs and planned construction needs is the recommended approach for updating the various elements included in the management system.

CHAPTER 10. SUMMARY

In this report, a framework has been proposed to replace the term "life" with a construction needs term relative to pavements. The objective of this proposal is to provide a more refined definition of future pavement construction needs that is easier to understand.

The major concepts presented in this report include the following:

- Current variability of pavement remaining life terminology is confusing.
- Since pavements are repairable systems, life terminology is not appropriate.
- The use of a terminology based on future corrective construction needs has the potential to replace pavement remaining life predictions.
- Prediction of future corrective pavement construction needs are based on the selection of construction trigger models that best represent factors used by an agency to schedule future treatments, the establishment of thresholds related to condition states of the construction triggers, and the development of performance curves that provide a prediction of the future change in pavement condition.
- Data collection should be based on providing needed input data to the construction trigger models.
- Network-level strategy selection should be based on LCC considerations and network optimization concepts.
- A continual cycle of improvement updates based on observations of past performance and introduction of new technology is required.

The framework concepts were formulated in terms that agencies can use to adapt and enhance their current practices.

Appendix A provides a general overview of pavement design and management concepts related to pavement life future construction events. Appendix B provides indepth reference citations on technical literature related to existing remaining pavement life models. These methods are equally applicable to construction needs terminology contained in this document. The bibliography contains the literature review summary developed by the project team during the project.

APPENDIX A. PAVEMENT DESIGN AND MANAGEMENT CONCEPTS

It is helpful to review pavement engineering design basics in order to develop a common terminology to apply to pavement life issues. In this appendix, the basic concepts of pavement design and management are reviewed to establish a framework for pavement remaining life definitions presented in this report.

PAVEMENT DESIGN BASICS

Figure 3 shows the basic concept of modern pavement design. This illustration starts with the construction of a new pavement structure. The pavement design life is the predicted time it will take for the structure to reach a minimum acceptable condition value. It is important to note that all current pavement design methods base the minimum acceptable condition on functional service criteria provided by a pavement structure and not an extreme condition that represents severe structural defects or prevents vehicle passage.

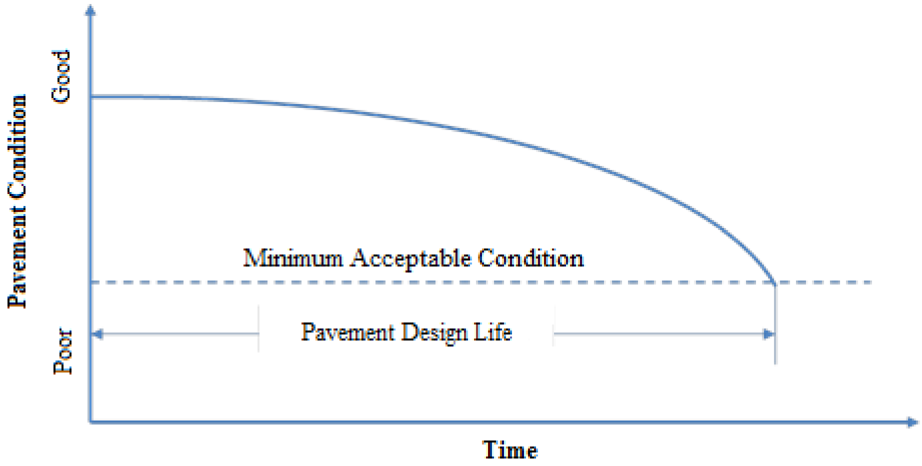

Figure 3. Graph. Basic concept of modern pavement design.

The definitions of pavement life cycle become more complicated when future pavement maintenance, restoration, rehabilitation, resurfacing, and reconstruction events are introduced into the design process

Figure 4 presents pavement design concepts from the 1986 *AASHTO Guide for Design of Pavement Structures* when the initial design life of an alternative pavement trial requires consideration of overlays to meet the required performance period or design life.(11) The Serviceability Index (SI) is used to measure pavement conditions. The design period or life is shown as time or accumulated traffic. In this example, the required performance period or design life exceeds the predicted life of the trial A pavement design. An overlay is required for trial A at the time its condition equals the minimum SI. The trial A1 overlay example does not satisfy the required performance period, while the trial A2 overlay is expected to exceed the required performance period. This is contrasted to the trial B pavement design that exceeds the required performance period without need for an overlay. In this case, the life of trial A is required to be extended with an overlay to achieve the desired performance period because the initial design life of trial A is less than required.

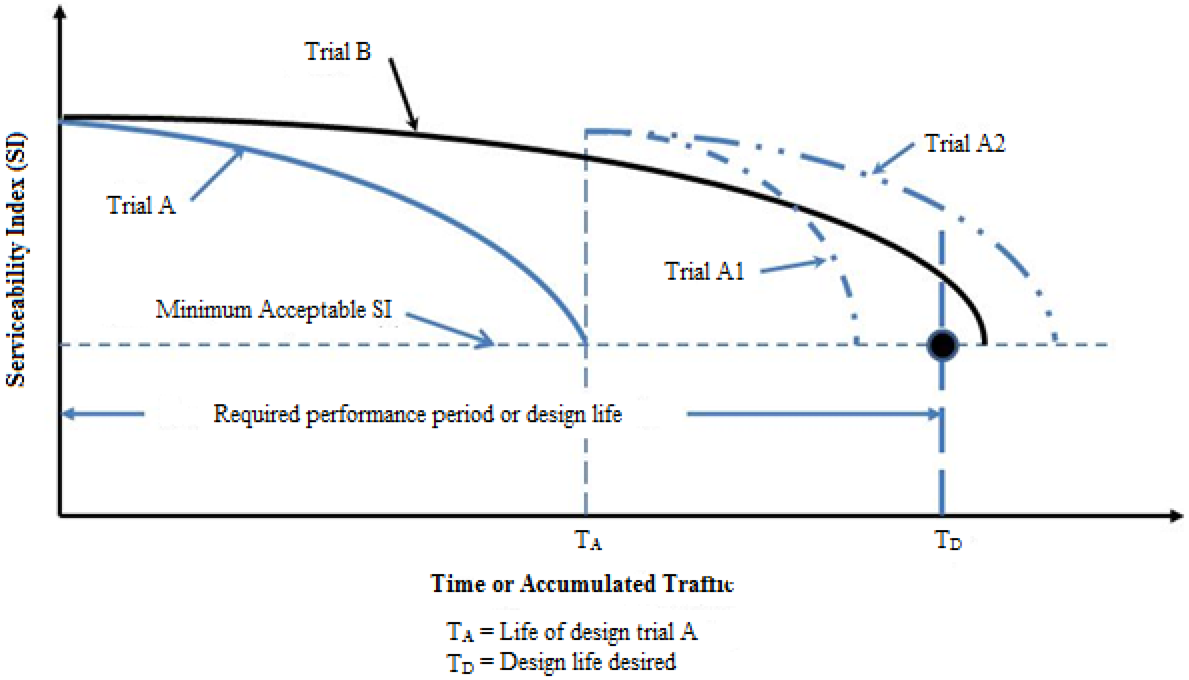

Figure 4. Graph. Illustrated service histories of trial pavement designs incorporating future overlays.(11)

STAGED CONSTRUCTION AND PERPETUAL PAVEMENTS

The concept of staged pavement construction was introduced to reduce initial pavement construction costs with the planned application of a structural overlay early in the life of a pavement to extend its life to a desired performance period. While the thickness of the initial pavement structure is initially constructed less than required, the added thickness of the overlay is applied early enough to meet the initial pavement design life requirements. This concept is illustrated in figure 5.

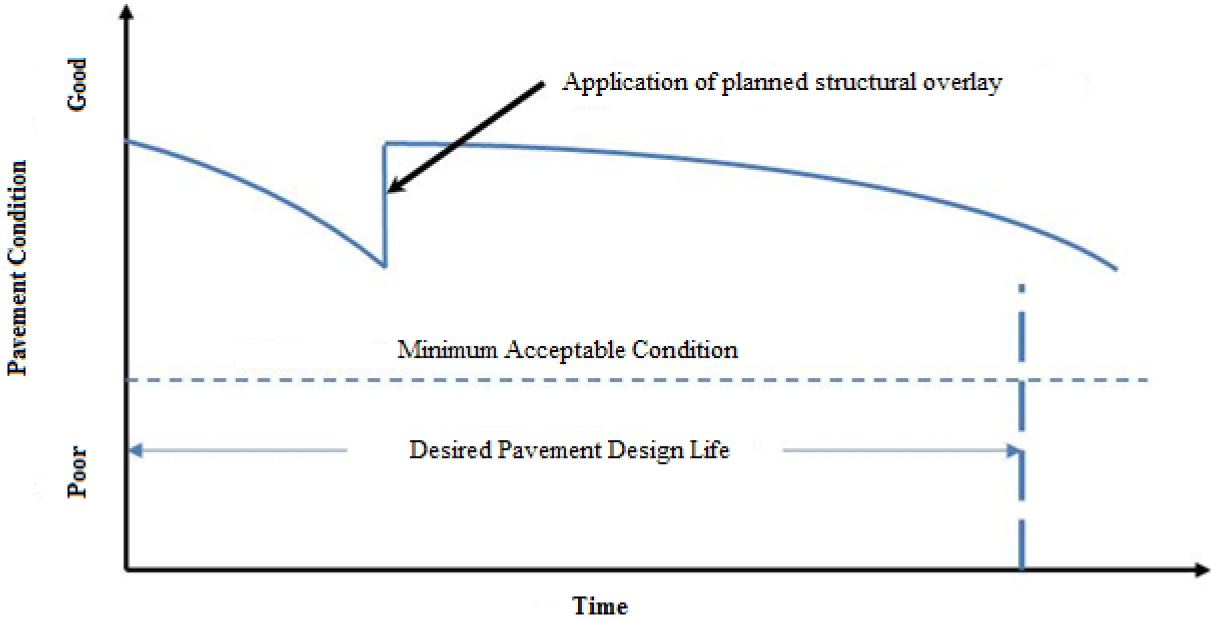

Figure 5. Graph. Staged pavement construction design concept.

A *perpetual pavement* is defined as an asphalt pavement designed and built to last longer than 50 years without requiring major structural rehabilitation or reconstruction and needing only periodic surface renewal in response to distresses confined to the top of the pavement.(12) The basic premise is that an adequately thick asphalt pavement placed on a stable foundation will resist distresses that form at the bottom of a pavement structure and are costly to correct. By limiting distress formation to the pavement surface layer, the pavement life can be extended in perpetuity by rejuvenating the pavement surface materials and remove and replace the type of maintenance operation, as illustrated in figure 6.

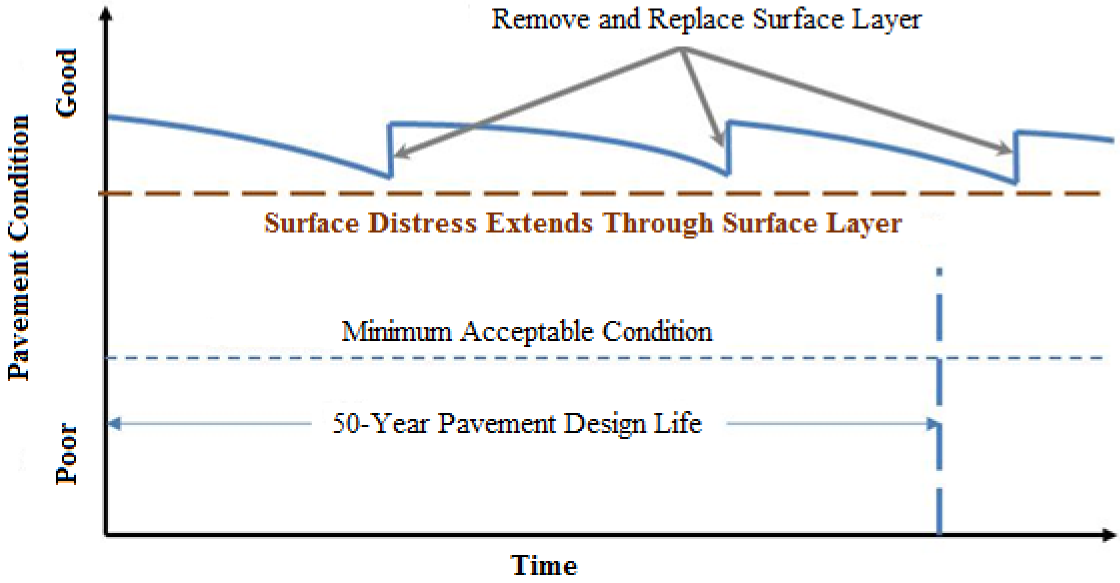

Figure 6. Graph. Perpetual pavement design concept based on construction of a pavement where distresses occur in the pavement surface layer.

MULTIPLE DISTRESS-BASED PAVEMENT DESIGN

Pavement design methods based on the development of multiple pavement distresses, such as the MEPDG, use multiple threshold values for each distress considered.(7) *Pavement design life* is defined as the shortest time it takes for one of the distresses to reach a terminal threshold condition. Figure 7 illustrates a hypothetical distress-based pavement design approach consisting of pavement roughness and two distress types. In this example, the pavement design life is defined by the time that distress 2 reaches the maximum tolerable threshold. Time to distress initiation is also illustrated in this figure. The time to distress initiation or first display of a distress feature such as cracking can be an important event in the pavement life for maintenance and repair planning activities and used to define maintenance-free time periods.

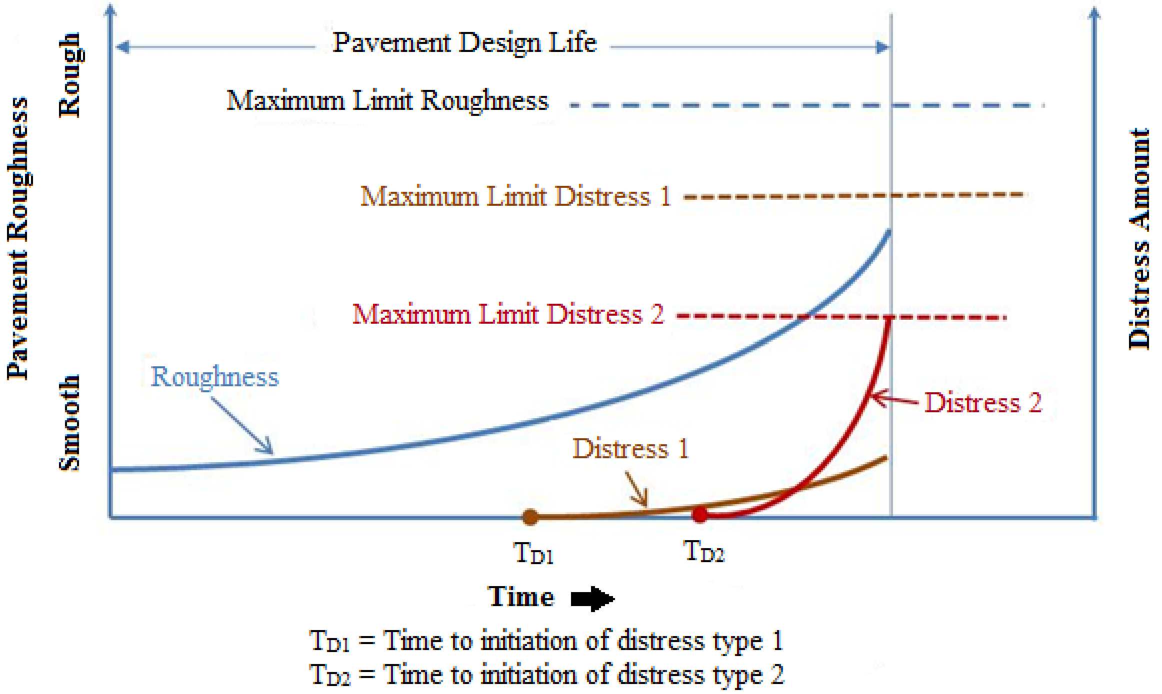

Figure 7. Graph. Multiple distress-based pavement design where one of the distresses reaches a maximum threshold limit.

REHABILITATION AND RECONSTRUCTION DESIGN

Selecting appropriate corrective treatments to restore the serviceability of a pavement depends on its condition at the time of application. As a pavement deteriorates, there comes a point when less costly rehabilitation treatments should not be applied, and the pavement must be reconstructed. Maintenance, repair, and preservation treatments have a tendency to be more cost effective if applied early in the life of a pavement before distresses cause damage to a pavement structure, which requires more costly rehabilitation treatments.

Figure 8 illustrates the general concept of application of corrective pavement treatments as a function of pavement condition. Unlike the other time-history pavement condition concept figures, the shape of the curve in this figure follows distress progression incorporated into some popular PMSs. This illustration contains three treatment zones as a function of pavement condition. The maintenance, repair, and restoration zone occurs early in the pavement life when distresses have not progressed to a state where a rehabilitation option, such as a structural overlay, is required. The rehabilitation zone occurs after maintenance, repair, and restoration treatments alone are effective and extends to the point where pavement reconstruction is required. The wait and reconstruct option represents allowing a pavement structure to deteriorate beyond what is considered functionally acceptable.

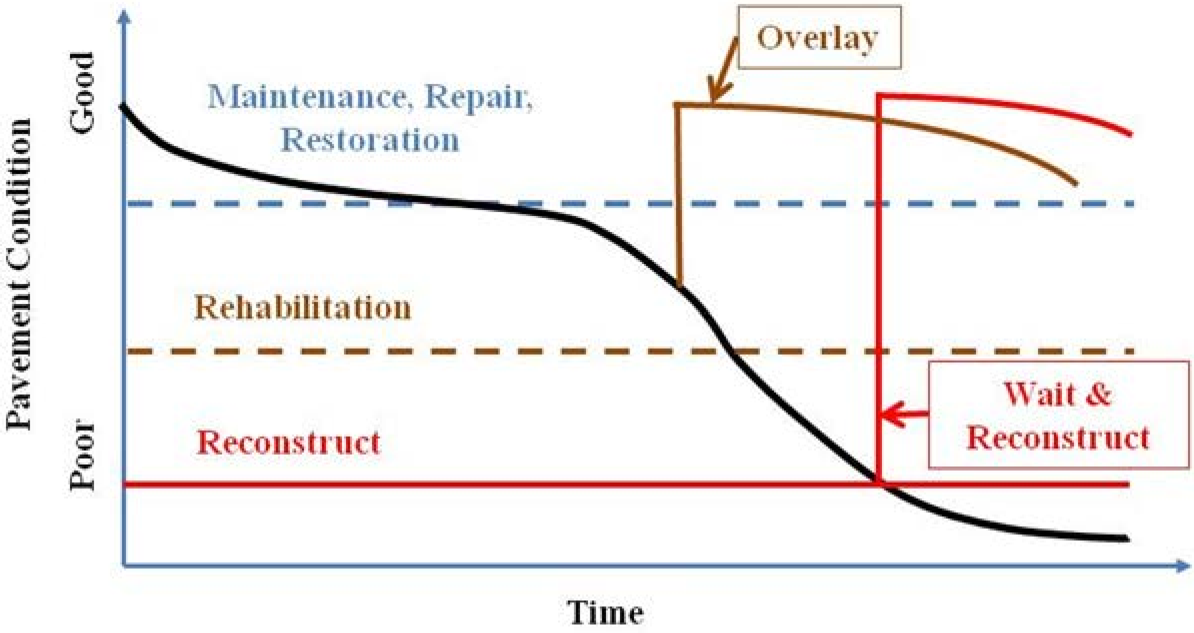

Figure 8. Graph. Three treatment zones as a function of pavement condition.

PAVEMENT ECONOMICS

LCCA is an engineering economic tool that is useful in comparing the relative merit of competing project implementation alternatives. By considering all of the costs (agency and user) incurred during the service life of an asset, this analytical process helps transportation officials select the lowest cost option or, more commonly, make tradeoff decisions. Additionally, LCCA introduces a structured methodology that accounts for the effects of agency activities on transportation users and provides a means to balance those effects with the construction, rehabilitation, and preservation needs of the system itself.(13) LCCA is the preferred approach used to determine pavement type choice and timing of preservation, rehabilitation, and reconstruction treatments.

Agency costs to construct and maintain pavement structures are, in practice, still the primary consideration in the pavement management process. Figure 9 illustrates the conceptual tradeoffs between pavement resistive capacity, construction costs, and maintenance, repair, and restoration costs that can be generated using LCCA. In this illustration, costs are expressed in total LCCs. Construction costs increase to provide a pavement structure with greater resistance to applied structural and environmental loads. For example, it costs more to build a thicker pavement structure to resist structural wheel loads and with better materials to resist environmental degradation. As the resistive capacity of the initial pavement structure increases, maintenance, repair, and restoration costs decrease. For a single pavement structure, a conceptual optimum pavement design exists at the minimum total pavement LCC. Under-designed pavements typically have a higher maintenance, rehabilitation, and repair cost ratio to construction cost than over-designed pavement structures.

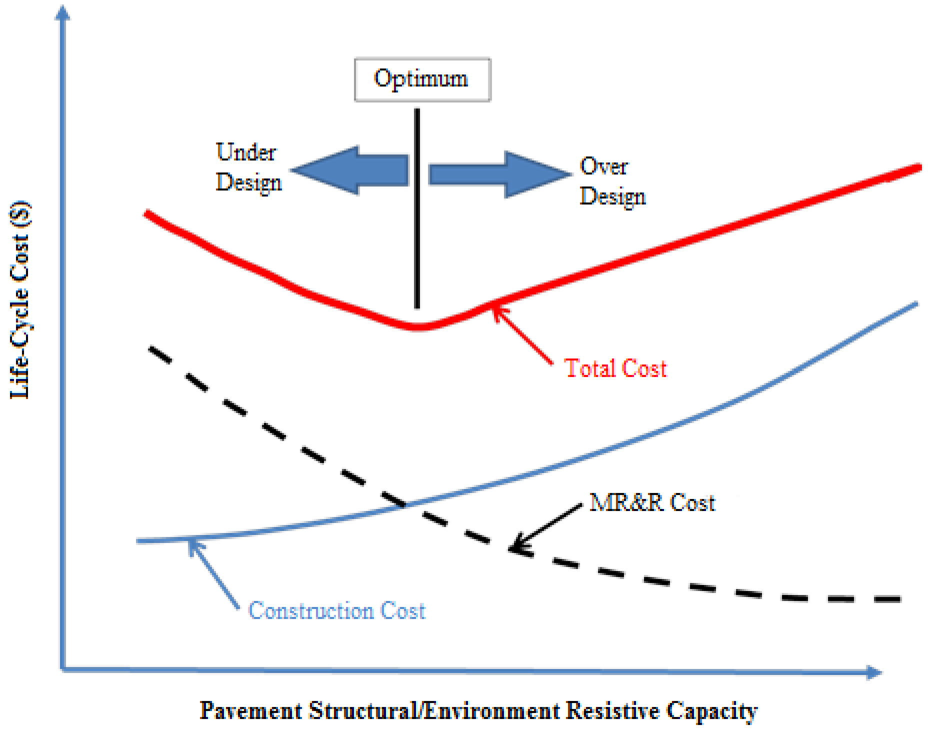

Figure 9. Graph. Conceptual tradeoffs among pavement resistive capacity, construction costs, and maintenance, repair, and restoration costs.

Figure 10 illustrates the economic concept of application of corrective pavement treatments. This concept is based on pavement deterioration rates accelerating as the pavement accumulates more damage. Because of the accelerated deterioration rate, the cost of deferring a treatment also increases at an accelerated rate.(14)

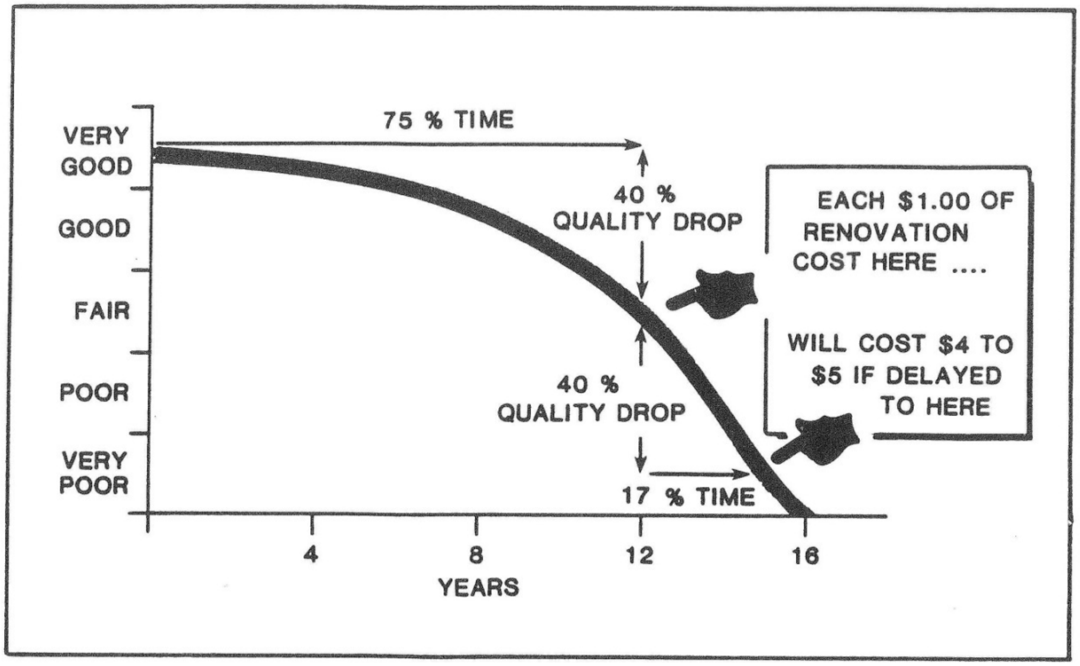

Figure 10. Graph. Concept of increasing repair cost as a function of pavement deterioration.(14)

SUMMARY

The following list summarizes pavement design, rehabilitation, and reconstruction concepts:

- Pavement design is based on providing a pavement that satisfies a functional service requirement relative to the role of the pavement structure in the transportation system.
- Application of maintenance, repair, preservation, and rehabilitation treatments can be used to extend the service provided by a pavement past the initial design life. Engineers implicitly or explicitly consider these actions during initial design stages.
- Some pavement design concepts are based on construction of a pavement structure so that renewal of the upper surface layer can provide a pavement structure that provides adequate serviceability as long as the renewal treatments are provided as needed.
- The initial design life of distress specific pavement design methods are based on one of the distresses reaching a terminal limiting threshold.
- Pavement condition thresholds are used to indicate when pavement rehabilitation treatments or reconstruction are predicted to be needed.
- A theoretical optimum mix of pavement construction, maintenance, and rehabilitation alternatives exists for each pavement structure.

APPENDIX B. PAVEMENT RSL PREDICTION MODELS

INTRODUCTION

This appendix presents a summary of major concepts from a literature review of pavement RSL and other industries related to life and product reliability. In the interest of brevity, equations for the various models and statistical mathematical forms have been left out of this review. Those interested in mathematical formulations can reference the citations contained in this report.

CATEGORIZATION OF RSL MODELS

The discussion of RSL prediction models requires a categorization scheme that groups models with similar features. The following methods have been used to categorize RSL prediction models:

- Witczak classified RSL estimation processes into the following categories: (1) functional failure-based approach, (2) structural failure-based approach, and (3) functional and structural failure-based approaches.(15)
- Yu used a primary category of mechanical/empirical analyses to classify RSL models. Secondary classifications using mechanical analyses included fatigue tests, punch out, and falling weight deflectometer (FWD) categories. Secondary classification using empirical analyses included regression, neural networks, nomographs, life table, Kaplan-Meier, failure time theory, and Cox PHs models.(16)
- Vepa et al. used functional failure-based and structural failure-based approaches as a primary classification to introduce survivor curve development.(17)

Prediction model classification schemes can also be based on the type of performance model. Empirical models are primarily founded on statistical approaches, while mechanistic-based models are primarily founded on engineering principles. These categories are not mutually exclusive; however, most of the mechanistic-based models use statistical methods for calibration, and some of the empirical models incorporate engineering principles.

LIFE TABLE SURVIVOR CURVES

The earliest known survival analysis for pavements in the United States was performed by Winfrey and Farrell.(18) The terminology used in the early years of this work was referenced to the life of the pavement surface. Survival curves were developed for pavements built each year from 1903 to 1937 in 46 States using the life table method. The distribution of survival times is divided into year or half-year intervals. For each interval, the mileage of pavement sections that were still in service in the beginning of the respective interval, the mileage of pavement sections that were out of service at the end of the respective interval, and the mileage of pavement sections that were lost (e.g., a road was abandoned) in the respective interval were counted. The survival probability of each interval was calculated by dividing the remaining mileage by the total mileage in the respective interval. A survival curve was formed by the probability versus time interval graph. RSL was estimated by extrapolating the survival curve to zero percent survival. The past use of the life table method for pavement RSL in the late 1940s, 1950s, and 1960s was documented.(19–21)

These are pure empirical models that apply to the inference space in which they were developed. They are not representative of changes in construction techniques, materials, traffic loads, or definitions of out-of-service pavements.

KAPLAN-MEIER SURVIVAL ANALYSIS

The Kaplan-Meier survival analysis method, also known as the product limit estimator method, is a statistical technique used to generate tables and plots of survivor or hazard functions for time-to-event data.(22) Advantages of the method are that it accounts for censored data, losses from the sample, and non-uniform time intervals between observations. The method assumes that events are dependent only on time. Since the method cannot differentiate between the life of a thin pavement with high traffic and a thick pavement with low traffic, pavements must be grouped into families that have similar characteristics, traffic loadings, and environments. In essence, a separate survivor curve has to be generated for each factor of interest. The method is incorporated in many popular statistical analysis packages and can provide a useful summary of available data in exploratory stages of research.

FAILURE TIME THEORY

The failure time theory has been used to develop survivor curves for pavements.(23,24) The basis of the failure time theory requires that the underlying functional form of the parametric failure distribution be assumed a priori. This allows for the estimation of the coefficients of those parameters, which in effect dictate the influential factors. However, this may not be feasible when the underlying functional form does not match any known parametric statistical distribution.

COX PH MODEL

The Cox PH model has been widely used in clinical trials to analyze the survival probability for patients after a treatment. The median survival time, which is defined as the time when 50 percent of the subjects will fail to maintain a specified physical condition, is often of interest. The distinctive feature of the method is that the ratio of the instantaneous risks of failure (i.e., the hazard ratio) at time *t* for any two given patients in the study does not change with time. The advantages of this method are that it does not require that the underlying survival distribution be known and the effects of influential factors on survival time can be estimated. A pavement is similar to a clinical trial in that after a period of time, it may fail to provide required serviceability after a treatment. A pavement is considered to have reached the end of its useable life if it is rehabilitated or if its condition falls below a specified criterion.(16)

This method has been used for life prediction in many areas of infrastructure management. Yu developed a Cox PH model for pavements in Ohio using the Ohio pavement condition rating. The rating is based on a 0 to 100 scale where 0 is poor and 100 is excellent. A score of 70 represents a failure condition. Some of the inferences implied by the models developed on this project are counterintuitive. The models are only applicable to the method ODOT uses to rate the condition of their pavements, traffic, and environmental conditions in Ohio as well as other attributes of Ohio pavements.

1986 AND 1993 AASHTO PAVEMENT DESIGN GUIDES

In the 1986 and 1993 versions of the *AASHTO Guide for Design of Pavement Structures*, pavement remaining life terminology is used in the overlay design methodology.(11,5) In the 1986 guide, two remaining life estimates are required for the analysis—the remaining life of the pavement prior to overlay and remaining life of the overlaid pavement when it reaches its terminal serviceability condition.(11) These remaining life values are expressed in terms of a percentage and are used to compute a remaining life factor. The remaining life factor is used to discount the effective structural capacity of the pavement prior to overlay in order to determine the structural capacity needs of the overlay. The 1993 guide uses a similar approach where remaining life is expressed as a percentage, but its use is simplified to determine the effective structural capacity of the existing pavement.(5) However, what is called pavement remaining life in these documents is really a way to estimate damage to the existing pavement structure and does not result in an estimate of the time until a terminal serviceability level is reached.

While the 1986 and 1993 versions of the *AASHTO Guide for Design of Pavement Structures* do not contain a procedure to estimate pavement life in terms of time until the next rehabilitation or reconstruction treatment is required, the design equations used in the methods can be used for this purpose.(11,5) These methods use two basic empirical design equations that relate the number of traffic loadings (expressed in terms of 18-kip (40-kN) equivalent single-axle loads (ESALs)) to pavement structural capacity, subgrade support properties, pavement serviceability changes, and reliability considerations. Estimating the time in years to the specific level of serviceability only requires inputs on the pavement structure layer types and thickness, subgrade properties, 18-kip (40-kN) ESAL applications to date, and the future rate of 18-kip (40-kN) ESAL applications. Using the design equations, the number of total applications the pavement structure can support until reaching the terminal serviceability level of interest is determined. Subtracting the total ESAL applied to the pavement from the total the pavement will support provides the remaining ESAL loadings until the terminal serviceability is reached. Dividing this by the ESAL rate per year provides a time estimate. The time to rehabilitation or reconstruction can be simulated by changing the terminal serviceability level. This is the approach that was previously used by the HPMS models as described in the next section of this appendix.

One of the more severe issues with using the older AASHTO pavement models for pavement remaining life analysis is that they are pavement design equations, which are not necessarily created as performance prediction models. Further, the models incorporated in the 1986 and 1993 AASHTO guides can be traced back to the AASHO Road Test.(11,5,4) The Road Test data inference space is severely limited.

HPMS/HERS MODELS

The remaining life models used for the HPMS analytical process and HERS model are changing. The initial models were based on the 1972 *AAHSTO Interim Guide for Design of Pavement Structures* equations.(8) This required pavement condition is expressed in terms of PSR and pavement structure capacity as SN for flexible pavements and slab thickness for PCC pavements.

Using this system, resurfacing or reconstruction was indicated by the level of PSR. When the pavement PSR in an analysis cycle dropped below a minimum tolerable condition based on highway functional classification, resurfacing was indicated. Reconstruction was triggered if the PSR dropped below the reconstruction threshold. The default minimum tolerable condition and reconstruction PSR values are shown in table 2.(25) For some rural facilities, the average daily traffic (ADT) was also used to discriminate the minimum tolerable condition, with lower volume facilities having lower trigger points. In the late 1980s data submittal requirements for pavement roughness measurements reported as IRI was added.

Table 2. PSR threshold values used in the HPMS analytical process for minimum tolerable conditions for overlay and reconstruction.

Location	Facility Type	Minimum Tolerable Condition (PSR)	Reconstruction PSR
Rural	Interstate	3.0	2.0
	Other principal arterial	3.0/2.8 (6,000 ADT)	2.0
	Minor arterial	2.4	1.5
	Major collector	2.0	1.1
	Minor collector	1.8	0.8
Urban	Interstate	3.2	2.2
	Other freeway and expressway	3.0	2.0
	Other principal arterial	2.8	1.8
	Minor arterial	2.4	1.1
	Collector	2.0	1.0

One of the outcomes of the reassessment of the HPMS in 2006 was the development of a new data model based on inputs related to the models used in the MEPDG.(7) Pavement-related data requirements were expanded and include the following:(26)

- IRI (annual cycle on NHS, 2 year cycle on non-NHS roadways).
- PSR (2-year cycle; no change).
- Rutting (2-year cycle).
- Faulting (2-year cycle).
- Fatigue cracking (2-year cycle).
- Transverse cracking (2-year cycle).
- Surface type.
- Year of last improvement.
- Year of last construction.
- Last overlay thickness (default values allowed).

- Flexible thickness (default values allowed).
- Rigid thickness (default values allowed).
- Base type (default values allowed).
- Base thickness (default values allowed).
- Soil type.
- Climate zone.

The development of simplified models for HERS and NAPCOM was reported by FHWA in 2007.(27) The objective of this work was to develop simplified models based on the MEPDG that could be used with HERS using HPMS data. The definition of RSL for this project is the time in age or traffic applications from initial construction or reconstruction to the first major rehabilitation. The following pavement distress prediction models were reported to be under development:

- JPCP.
    - Transverse cracking.
    - Joint faulting.
    - Joint spalling.
    - Pavement smoothness—IRI.
- HMA and HMA overlay pavements.
    - Alligator cracking.
    - Wheel path rutting.
    - Transverse cracking.
    - Pavement smoothness—IRI.
- Composite pavement.
    - Transverse reflection cracking.

A key concept in applying these models was to adjust the predictions from the MEPDG design models to current observations contained in the HPMS dataset. It appears that the magnitudes of the predicted distress level from the model were adjusted to the field observations, and future predictions were based on the rate of increase according to pavement age.

Recently, FHWA has developed a PHT analysis tool for HERS and NAPCOM purposes that uses HPMS data.(28) Models based on use of the default level 3 MEPDG inputs along with the HPMS data are used to predict changes in the multiple pavement condition measures adjusted for current observed levels. In this application, *pavement health* is defined as the time in age or load applications from initial construction or reconstruction to the first major rehabilitation as warranted by pavement ride and structural conditions. The following distress prediction models are included in the tool:

- New HMA and HMA overlay of existing HMA.
    - Alligator cracking.
    - Rutting.
    - Transverse cracking.
    - Smoothness—IRI.
- New JPCC.
    - Transverse cracking.
    - Transverse joint faulting.
    - Smoothness—IRI.
- Composite—HMA overlay of existing PCC.
    - Reflection cracking.
    - Smoothness—IRI.

OTHER CONTEMPORARY PAVEMENT RSL MODELS

The following examples highlight contemporary RSL models developed within the pavement engineering community:

- George developed a graphical procedure to determine RSL based on the effective thickness ratio derived from nondestructive deflection testing.(29)
- Mamlouk et al. computed RSL based on a fatigue model (considering the rate of crack development in Arizona) in conjunction with the backcalculated moduli.(30)
- Huang used two general mathematical distress models to determine the remaining life of flexible pavements.(31)
- Park and Kim and Werkmeister and Alabaster developed RSL models based on FWD measurements.(32,33)

- Santha et al. developed a simple, mechanistic rut-depth prediction model that, when used with estimated current traffic, yields the RSL.(34)
- Ferregut et al. and Abdallah et al. applied artificial neural network techniques to develop algorithms that combine the functional condition of a pavement (i.e., percent cracking and depth of rut) at the time of FWD testing with simple remaining life algorithms to predict the remaining life of pavements.(35,36)
- Zaghloul and Elfino used backcalculated layer moduli and expected traffic volumes to estimate the RSL of homogeneous sections.(37)
- Gedafa proposed sigmoidal RSL models that can predict flexible pavement RSL based on the center deflection from FWD or rolling wheel deflectometer and also take into account pavement factors such as layer thickness, traffic, distress, and structural data.(38)

Many of the approaches discussed have great potential to be used at the project level. Due to the mechanistic approach of most of these contemporary models, they also have potential to be used for public-private partnership-type projects as the results are scientifically based and are likely defensible from both the agency and concessionaire perspectives. Used with a cost estimating model, these methods could be used to determine the remaining value of a given project.

Many mechanistic approaches rely on determining the structural response of a pavement from the various devices that measure the deflection of a pavement surface under various types of applied loads. The Long-Term Pavement Performance (LTPP) program has shown that deflection measurements possess seasonal variability in the measured responses that can introduce uncertainty if corrections are not made for these effects. By definition, preservation treatments do not add structural strength to the pavement section. As a result, deflection measurements do not account for the increase in service life provided by preventative treatments.

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM (NCHRP) PROJECT 08-71

NCHRP Project 08-71, *Methodology for Estimating Life Expectancies of Highway Assets*, began in July 2009.(39) The objectives of this research were to develop a methodology for determining the life expectancies of major types of highway system assets for use in LCCA supporting management decisionmaking; demonstrate the methodology's use for at least three asset classes, including pavement or bridges and two others, such as culverts, signs, or signals; and develop a guidebook and resources for use by State transportation departments and others for applying the methodology to develop highway maintenance and preservation programs and assess the impact of such programs on system performance.

Pavement was one of the assets studied under this project. The following information concerning pavement life expectancy was obtained from *NCHRP Report 713: Estimating Life Expectancies of Highway Assets, Volume II: Final Report*.(40) Traffic loading in particular has been studied with field tests for trucks with various suspensions for both static and dynamic loads. Traffic loading is considered a better indicator of service life than age, although there is a correlation between the two factors; reliability curves built on traffic loading are often used to predict service life. Other than traffic loading, the amount of distress is primarily utilized. To determine the most influential distress type, studies have used a discriminate analysis approach. Depending on the pavement type (e.g., asphaltic, concrete, gravel, etc.), additional factors affect the life expectancy.

For pavements, factors that affect life expectancy include surface type (i.e., rigid, flexible, and composite), design and construction features, traffic loading, climate, age, frequency, and intensity of pavement M&R. For each surface type, the project will consider the different pavement subtypes and thicknesses. The influence of traffic loading will be investigated on the basis of the load spectra. Also, literature will be reviewed on the influence of vehicle dynamics to gain information on the expectations from the analyses of life expectancy sensitivity to operations. The impact of climatic severity on pavement life expectancy will be expressed in terms of variables such as freeze index, average temperature, and the number of freeze-thaw transitions. The incorporation of M&R activities will be done by determining the impact of specific M&R treatments on life extension and determining the impact of different M&R annual expenditures (cost per lane-mile) on life extension. The final selection and analysis of influential factor sensitivities will be guided by the availability of data. Methods for assessing the sensitivities will include the Cox PH model.

FRICTION

The forecasting of friction is typically performed as a function of environmental variables in an effort to predict skid resistance throughout changing weather conditions and seasons. There are many models that currently accomplish this goal, but they do not forecast long-term conditions. In order to incorporate surface friction characteristics into a pavement life discussion, the focus must be on the long-term trend in friction.

Several models have been proposed to predict future skid resistance-based on factors such as material properties, traffic loading, and age. Using data from Toronto highways, Emery developed an equation in 1982 based on Marshall stability, Marshall flow, mix air voids, and a commercial vehicle equivalency factor.(41)

The Wisconsin Department of Transportation developed models in 1996 that predict friction number (FN) at 40 mi/h (64 km/h) based on aggregate properties and traffic characteristics for HMA and PCC surfaced pavements.(42) Independent variables include percent dolomite in the coarse aggregate, Los Angeles wear rate, accumulated vehicles passes, and percent heavy vehicles.

A 2006 study using Maryland SHA skid data suggests a much simpler prediction model based on the age of the pavement.(43) The authors show that FN at 40 mi/h (64 km/h) decreases approximately 0.22 FN per year on rural roads and 0.26 FN per year on urban roads. These rates are valid only after an initial period of high friction loss (approximately the first year).

The development of pavement age/traffic application friction models were reported by Ahammed and Tighe in 2009.(44) Two models each for AC and PCC surfaced pavements were developed based on either pavement age or cumulative traffic passes. These models are based on LTPP data, which has a much broader geographic scope than many of the other models, which are typically based on local/regional datasets. These models use a speed term to predict skid number at different speeds instead of modeling skid number at just one speed. A unique observation modeled in this work is that pavement friction will essentially reach a steady state and not continue to degrade with more traffic or age. Although not incorporated into the models, the authors also suggest that friction will start to increase as the pavement reaches old age due to degradation of the pavement surface through mechanisms such as raveling on AC pavements.

Synthesis reports in 2000 and 2005 document agency practice with respect to acceptable friction values.(45,46) Agencies tend to have FN threshold limits between 20 and 30, but those limits are typically accompanied by other factors such as crash history or a known friction problem.

The friction threshold in current practice is for maintenance activity, not rehabilitation or reconstruction. Treatments such as diamond grinding, open-graded friction course, chip seal, or simply posting signage to indicate a low friction area are often used. However, there is no indication that any agency currently uses surface friction characteristics as a part of pavement life determination.

NOISE

The goal of noise prediction is to predict noise at some location away from the roadway given a particular noise level at that roadway. None of the major models attempt to predict noise at some future point in time, as it is not considered a necessary factor in determining pavement life.

Similar to friction, there is no indication that agencies use noise as a factor in determining pavement life, and the actions taken in cases of excess noise are not rehabilitative in nature. Surface treatments such as grinding, grooving, and thin overlays of various types are used to improve noise characteristics along with external remedies such as sound barriers and other roadside design features.(47,48)

CONCEPTS FROM OUTSIDE THE PAVEMENT INDUSTRY

The body of literature from outside the field of pavements provides a rich source of information on theoretical models and terminology that are relevant to pavements. The following list provides some key concepts captured by the study team from a review of available information outside the field of pavements:

- A repairable system can be restored to satisfactory operation by any action, including parts replacements or changes to adjustable settings. Failure rates and hazard rates only refer to the first failure times for a population of non-repairable components.(49)
- In a non-repairable population, individual items that fail are removed permanently from the population. While the system may be repaired by replacing failed units from either a similar or a different population, the members of the original population dwindle over time until all have eventually failed.
- Lifetime distribution models are theoretical population models used to describe unit lifetimes. The population is generally considered to be all possible unit lifetimes for all

units that could be manufactured based on a particular design, choice of materials, and manufacturing process.

- Alternate types of probability density functions (PDFs) are used to describe lifetime distribution models.

- A cumulative distribution function is the probability that a unit will fail between times defined by the PDF. It is the integral, or area under the PDF curve, between time events in the PDF.

- The reliability function or survivability function are defined by the probability that a unit survives beyond a specified time. The general rule is to calculate the reliability of a system of independent components and multiply the reliability functions of all the components together.

- Failure rate is defined for non-repairable populations as the (instantaneous) rate of failure for the survivors to time during the next instant of time. The failure rate is sometimes called a conditional failure rate since the population of survivors used in the denominator converts the expression into a conditional rate, given survival past time.

- The concept of virtual age accounts for the effect of the repair strategy on future system performance modeling. If a repair returns a system back to an initial state of performance, the virtual age of the system is reset to zero. At the other extreme are minimal repairs that have no impact on future performance of the system and the virtual age is equal to the actual age of the system.(50)

For many years and across a wide variety of mechanical and electronic components and systems, empirical population failure rates have been calculated as units of age over time and repeatedly obtained the "bathtub curve," which illustrates instantaneous failures rates over a product's life. The bathtub curve concept is depicted in figure 11 and has three distinctive time periods: the early life or infant mortality period, constant failure rate or useful life period, and end-of-life or wear out period. The high rates of failure during the early life or infant mortality period are characteristics of weak units with manufacturing or other defects. The early period is followed by a period of relatively constant failure rate also known as the intrinsic failure, normal, or useful life period. During this period, failures tend to be more random in nature due to various effects that impact life depending on the type of component. This is followed by the wear out period when the failure rate increases at the end of the product life.

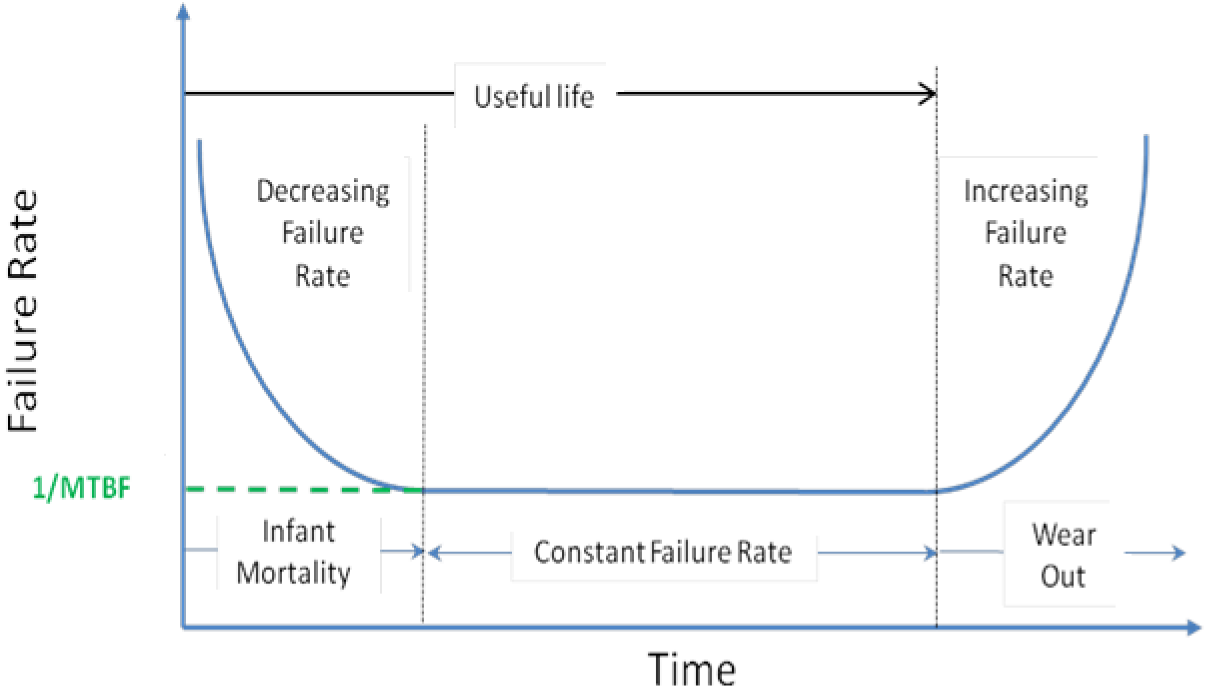

Figure 11. Graph. Classical bathtub curve of component failure rate versus time.

The bathtub curve is expressed as a function of failure rate. Failure rate is expressed in units of failure per component-time. Standards for the mean time between failures (MTBF) statistic are defined as the reciprocal of the failure rate during the constant rate failure period when the failure rate is a minimum value.(51) In many interpretations, the component part of the statistics is not stated and the units are expressed as time/failure, which can be deceiving since it has no direct relationship to the life of a product. For example, it is possible for a product to have a MTBF exceeding 100 years since it is based on the minimum failure rate but have a life expectancy of less than 10 years based on the time until the electrical component or system actually fails. Although MTBF is useful for relative comparison of different components or devices, it is not an indicator of expected life.

A comprehensive and continuously updated source of information the project team found comes from the National Institute of Standards and Technology and Semiconductor Manufacturing Technology *NIST/SEMATECH e-Handbook of Statistical Methods*.(49) The following list contains information on the various concepts and models from this handbook:

- Repair rate models are based on counting the cumulative number of failures over time. Time is measured by system power-on hours from initial turn-on at time zero to the end of system life. Failures occur at given system ages, and the system is repaired to a state that may be the same as new, better, or worse.
- The repair rate or rate of occurrence of failures is the mean rate of failures per unit time or the first derivative of average or expected number of failures for each time segment.
- Acceleration models predict time to failure as a function of stress. Acceleration factors show how time-to-fail at a particular operating stress level (for one failure mode or

mechanism) can be used to predict the equivalent time to fail at a different operating stress level. Acceleration models are usually based on the physics or chemistry underlying a particular failure mechanism. Successful empirical models often turn out to be approximations of complicated physics or kinetics models when the theory of the failure mechanism is better understood. Some acceleration models are as follows:

  - Arrhenius model predicts failure acceleration due to temperature increase.
  - The Eyring model has a theoretical basis in chemistry and quantum mechanics and can be used to model acceleration when many stresses are involved.
  - The Coffin-Manson model is a useful non-Eyring model for crack growth or material fatigue.

- The following parametric models have successfully served as population models for failure times arising from a wide range of products and failure mechanisms. Some models are probabilistic arguments based on the physics of the failure mode that tend to justify the choice of model. Other models are used solely because of their empirical success in fitting actual failure data.
  - The exponential model, with only one unknown parameter, is the simplest of all life distribution models. The exponential model is used for the flat portion of the bathtub curve, where most systems spend most of their lives. Mathematical equations can be found in section 8.1.6.1 of the *NIST/SEMATECH e-Handbook of Statistical Methods*.(49)
  - The Weibull model is a very flexible life distribution model with two basic parameters that can be increased to three by introducing a waiting time parameter. Because of its flexible shape and ability to model a wide range of failure rates, the Weibull model has been used successfully in many applications as a purely empirical model. The Weibull model can be derived theoretically as a form of extreme value distribution, governing the time to occurrence of the weakest link of many competing failure processes. Mathematical equations can be found in section 8.1.6.2 of the *NIST/SEMATECH e-Handbook of Statistical Methods*.(49)
  - Extreme value distributions are the limiting distributions for the minimum or the maximum of a very large collection of random observations from the same arbitrary distribution. In the context of reliability modeling, extreme value distributions for the minimum are frequently encountered. The extreme value distribution is useful for modeling applications for which the variable of interest is the minimum of many random factors, all of which can take positive or negative values. Mathematical equations can be found in section 8.1.6.3 of the *NIST/SEMATECH e-Handbook of Statistical Methods*.(49)
  - The lognormal life distribution, like the Weibull model, is a very flexible model that can empirically fit many types of failure data. The lognormal model can be theoretically derived under assumptions matching many failure degradation processes

  common to electronic (semiconductor) failure mechanisms. Some of these are corrosion, diffusion, migration, crack growth, electromigration, and, in general, failures resulting from chemical reactions or processes. Mathematical equations can be found in section 8.1.6.4 of the *NIST/SEMATECH e-Handbook of Statistical Methods*.(49)

  - The gamma distribution is a flexible life distribution model that may offer a good fit to some sets of failure data. The gamma is used in standby system models and also for Bayesian reliability analysis. The chi-square distribution is a special case of the gamma distribution. Mathematical equations can be found in section 8.1.6.5 of the *NIST/SEMATECH e-Handbook of Statistical Methods* (49)

  - The 1969 Birnbaum and Saunders fatigue life distribution model is based on a physical fatigue process where crack growth causes failure. The Birnbaum-Saunders assumption, while physically restrictive, is consistent with a deterministic model from materials physics known as Miner's Rule or Miner's Hypothesis. Mathematical equations can be found in section 8.1.6.6 of the *NIST/SEMATECH e-Handbook of Statistical Methods*.(49)

  - The Cox PH model has been used primarily in medical testing analyses to model the effect of secondary variables on survival. It is more like an acceleration model than a specific life distribution model, and its strength lies in its ability to model and test many inferences about survival without making any specific assumptions about the form of the life distribution model. This type of model was developed to predict the remaining life of pavements in Ohio using a PCI type of rating system.(16)

As documented in the literature review performed for this project, many of these concepts and statistical distributions have been used in the pavement industry to predict pavement performance and time until intervention is required.

The terminology and statistics related to repairable systems offer a good theoretical basis for future development of pavement RSL models. A pavement is a repairable system. The concept of virtual age of a system appears to have some applicability to pavements. Some examples of the application of the virtual age concept to improvement of pavement models include the following:

- Pothole patching is a minimal repair that does not change the rate of damage accumulation along the structure. The virtual age of the pavement system is still equal to the actual age after patching of spot surface defects.

- Replacement of the upper surface layer of an AC/HMA pavement designed for top-down cracking before the cracks extend too deep into the bound portions of the pavement structure is an example of a repair that can return a system to a new condition and reset the virtual age of the system to zero in terms of distress prediction models.

- Mill and overlay repair techniques fall somewhere between the minimal and perfect repair scenarios. While these repairs do not return the pavement system to a "good as new condition," they should reduce the virtual life starting point in a RSL model by some fraction. In other words, while the repair/treatment does not return the pavement to good as new status, it should retard the distress rate to an earlier virtual model age.

- Most pavement reconstruction activities can be considered as repairs since they tend to only affect the upper bound portions of a pavement structure. The parts of the pavement system related to embankments, base layers, subsurface, and surface drainage features tend to not be changed unless they are identified as a significant contributor to the cause of pavement degradation.

LITERATURE REVIEW OBSERVATIONS

The following observations are based on the literature review of pavement RSL models and concepts from outside the pavement industry related to the objectives of this project:

- General empirical population models based on concepts such as survivor curves are applicable only to the population on which they are based. The basis for these statistics tends to be ill-defined and do not account for changes in pavement technology. One must wait more than 10 years for this type of statistical inference base to catch up with technology changes.

- Current pavement service life prediction models are by necessity specific to the condition measurement system on which they are based.

- Pavement condition prediction models are specific to the condition and inference space for which they were created. This means that a model based on a measurement standard used in one jurisdiction is only applicable to agencies that use the same measurement standard and have similar types of pavement structures, with similar age, materials, and traffic/environmental conditions.

- In this review, pavement surface friction is treated as a defect repairable by maintenance types of treatments. Pavement noise prediction models are rarely associated with a pavement life history model that associates increased noise as a function of pavement structure age. While pavement surface texture can affect noise generation, pavement noise is not a first order consideration in the application of pavement treatments.

- Modeling terminology and concepts based on repairable systems from literature appear to be a good basis for future developments in pavement condition modeling. The virtual system age concept related to the impacts of maintenance, repair, and restoration treatments offers a good nomenclature framework to describe the effects of pavement corrective treatments.

- Advanced statistical modeling techniques exist for system reliability based on a defined numerical measurement system and nomenclature related to repairable systems.

- A common issue in all service life models both within and outside the pavement industry is the basis for failure threshold limits. The SI developed at the AASHO Road Test used a human panel to rate pavement acceptability.(4) Subjective ratings are known to change with time, technology, location, visible maintenance features, in-vehicle noise, and other conditions. Combined distress indices often use threshold limits whose basis is not well documented or hard to find. One study of acceptable road roughness found that 15 percent of users found roughness levels higher than 170 inches/mi (2.7 m/km) to be acceptable, although this is still a suggested threshold value for roughness.(52)

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