Development of a Risk Module for Enhancing Pavement Management Analysis

Fadi Jadoun, Leanne Whiteley-Lagace, Gabe Cimini, Allan Venema
Stantec Consulting, Ltd.
Chandler, AZ
Fadi.Jadoun@stantec.com

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Abstract

Infrastructure owners and operators are increasingly adopting risk-based pavement management to enhance traditional condition-driven approaches. This paper presents the development of a risk-based analysis module, integrated into Stantec's proprietary RoadMatrix™ Pavement Management System (PMS) to allow users to prioritize maintenance and rehabilitation (M&R) work programs based on risk and/or the traditional performance-based approach. A "Risk Score" is calculated from Probability of Failure (PoF) and Consequence of Failure (CoF) indices which have been carefully proposed and implemented as part of this development. A risk-based pavement M&R analysis ensures that critical road sections are identified and addressed proactively. Ten weighted factors define the PoF (e.g. age, predicted condition, traffic and climate exposure) and ten define the CoF (e.g. safety hazards, traffic disruption, economic impact). Each pavement segment's Risk Score (0–100 scale) is mapped to a Risk Level from Very Low to Extreme, which triggers appropriate M&R actions (from routine monitoring to immediate rehabilitation or replacement). This paper describes the framework's motivation—namely, overcoming limitations of condition-only prioritization, along with the module's methodology, implementation within the RoadMatrix™ PMS, and an illustrative application. Results demonstrate a more transparent and defensible network-level M&R plan: high-risk segments (e.g. heavily trafficked roads in poor condition) are prioritized for intervention, optimizing safety and lifecycle outcomes. The risk-based module enables agencies to allocate resources more strategically, justify decisions to stakeholders, and comply with risk-based asset management mandates. Benefits, limitations, and future enhancements (such as quantifying unmeasured benefits as a result of adopting a risk-based approach) are also discussed, positioning this work as a practical advancement in pavement asset management.

Introduction

Infrastructure owners and operators have traditionally prioritized pavement maintenance and rehabilitation (M&R) using condition indices, e.g. Pavement Condition Index (PCI), as the primary basis for decision-making. Recognizing the limitations of condition-only prioritization, Stantec developed its RoadMatrix™ Pavement Management System (PMS) decision tree approach to enable incorporation of a

virtually unlimited number of user-defined fields. In addition to surface condition, represented by PCI, RoadMatrix™ decision trees can incorporate section-specific attributes to reflect local practices, available treatment optsions, and pavement management principles. These attributes may include, but are not limited to the pavement age, last applied treatment, geometric elements (e.g., curbs presence, cross slope), subgrade condition, traffic data (e.g., bus route, truck route, emergency route).

While condition-based approaches are useful, they do not account for the varying criticality of different road segments. For example, a low-volume local road in poor condition may receive the same priority as a high-volume arterial in slightly better condition, even though failure of the arterial would result in substantially greater disruption and safety risk. This limitation has contributed to a shift toward risk-based pavement management, which considers not only the extent of deterioration, i.e., “How bad is the pavement?”, but also the consequences associated with the loss of service life, i.e., “What happens if it fails?”.

Recent transportation asset management policies and research emphasize the integration of risk into infrastructure decision-making. In the United States, federal regulations mandate each state Department of Transportation (DOT) to develop a risk-based asset management plan for highway infrastructure[1], underscoring that risk analysis is no longer optional but essential in asset management.

In practice, risk is typically defined by two components: (1) Probability of Failure (PoF), defined as the likelihood or probability that an asset will rapidly deteriorate or fail within a given time; and (2) Consequence of Failure (CoF), defined as the impact or severity of outcomes or impacts should failure occur. Incorporating PoF and CoF provides a more comprehensive representation of network needs. Risk-based asset management has gained prominence in recent years as agencies seek to address performance uncertainty and reduce the likelihood of missing strategic targets[2]. However, fully quantitative risk analysis can be data-intensive and complex. Many agencies thus adopt semi-quantitative methods – combining expert judgment and available data to score risk – as a practical compromise.

This paper presents the development of a risk-based analysis module within Stantec’s RoadMatrix™ PMS that generates recommended M&R work programs triggered by a composite Risk Score, amongst other performance indices and site-specific attributes. The goal is to enhance the traditional PMS decision logic by prioritizing high-risk segments even when their condition is not the worst, while enabling safe deferral of interventions on low-risk segments. This paper details the conceptual framework and methodology of the risk module, including the selection and weighting of the PoF and CoF factors, computation of a normalized Risk Score, classification into discrete risk levels, and integration into the PMS workflow. An illustrative example demonstrates the influence of the Risk Score on network-level predicted performance and recommended M&R programs. Practical benefits for agencies, from improved safety outcomes to strengthened budget justification, current limitations, and possible enhancements are also discussed. CThe intent is to provide a practical implementation of risk-based pavement management suitable for transportation agencies and to support broader adoption of risk-informed asset management practices[1].

Background: Risk-Based Pavement Management

Risk-based pavement management combines engineering judgment with risk management principles to improve network-level M&R treatment recommendations. Rather than relying solely on pavement

condition, pavement structure, and site-specific attributes, it introduces a systematic method to evaluate the likelihood pavement failure and the consequences if failure occurs. This approach aligns with broader asset management frameworks (e.g., ISO 55000[5] series and federal Transportation Asset Management Plans (TAMP)) that call for risk assessment as a core element of decision-making[3]. In essence, agencies are encouraged to allocate resources not only to "the worst first" pavements, or solely to preservation of good pavements, but to assets that pose the greatest risk to service, safety, and cost objectives if left unaddressed.

In the pavement context, PoF corresponds to factors that increase the likelihood that a pavement segment will reach a failure or very poor condition in the near term. CoF corresponds to factors that determine the impact or criticality of that failure. By evaluating both factors, agencies can compute a Risk Score for each road segment. This approach is consistent with risk assessment approaches used in other infrastructure domains, and infrastructure owners and operators are increasingly incorporating risk-based analyses into their asset management systems.

Recent practice across North America demonstrates a shift from condition-driven pavement management toward risk-based approaches that directly inform M&R decisions. In Canada, municipalities such as Sault Ste. Marie[6], Thunder Bay[7], and Thorold[8], Ontario, have incorporated formal risk frameworks into their asset management plans to prioritize interventions and optimize lifecycle strategies. Similarly, in the United States, agencies including Vancouver, Washington[9] Schenectady, New York[10], are advancing their pavement management systems by integrating risk considerations into their M&R treatment selection. At a broader level, requirements established by the Federal Highway Administration (FHWA)[11] mandate risk-based transportation asset management planning. Collectively, these examples illustrate how risk-based methodologies are increasingly embedded within pavement management systems to support proactive, cost-effective, and defensible M&R decision-making. Purely condition-based plans may inadvertently allow critical assets to be deferred if condition alone do not trigger timely intervention. By quantifying risk, agencies can more clearly justify why a moderately distressed but high-consequence urban arterial may warrant higher priority than a severely distressed low-volume road. Explicit risk computation can also improve transparency by demonstrating how factors such as safety or traffic disruption influence maintenance priorities, thereby supporting communication of investment decisions to stakeholders and the public.

RoadMatrix™ Risk Module Development Framework

Weighting Philosophy

Risk is defined as a function of Probability of Failure (PoF) and Consequence of Failure (CoF). For the RoadMatrix™ Risk Module implementation, ten (10) PoF factors and ten (10) CoF factors were selected. The chosen factor weights reflect a deliberate policy emphasis: higher weights on safety and mobility ensure that segments with the potential to generate crashes or major delays will receive a high CoF score, even when current condition remains in good condition. Conversely, factors like environmental and reputational considerations, while important, were assigned lower weights so that they do not overshadow core transportation service impacts. RoadMatrix™ allows weighting scheme to be adjusted by agencies to reflect local priorities. For example, a city concerned about bicycle traffic might increase the weight on Pedestrian and Cyclist Risks. The current weights were developed through expert workshops and are consistent with common practices (for instance, other municipalities have used similar factor sets and multiplied PoF/CoF values in their asset management optimization[6] [7]).

Probability of Failure (PoF) Factors and Weights

Probability of Failure (PoF) represents the likelihood that a pavement section will fail, or fall below an acceptable condition threshold, within the near future. Ten (10) key factors influencing pavement failure probability as well as their weights were identified through a combination of established pavement engineering principles, feedback received from clients (e.g., experience with using low quality material and/or bad workmanship), the availability of data within the pavement management system (PMS), and the practicality of acquiring the data when it is not already available. The process of selecting these factors was further informed by the professional judgment and experience of Stantec pavement specialists.

Table 1 provides a summary of the ten (10) PoF factors, including their assigned weight, which reflect each factor's relative contribution to the overall PoF score and collectively sum to 100%, as well as the number of categories, data type, and applicable value ranges for each factor.

Table 1. RoadMatrix™ Probability of Failure (PoF) Factors and Associated Weights

PoF Factor	# of Categories	Data Type	Value Range	Weight (%)
Age Since New or Last Reconstruction (years)	5	Numerical*	3 – 20+ Years	10
Predicted PQI	5	Numerical*	20 -100	25
Count of Annual Freeze/Thaw Cycles	7	Numerical*	0 – 90+	10
Structural Design Adequacy	5	Descriptive	Good Materials + Conservative Design – Poor Materials + Under design	8
Construction Quality /Workmanship	4	Descriptive	Very Poor - Superior	5
Subgrade Conditions	3	Descriptive	Weak, Fair, Strong	10
Daily ESAL	9	Numerical*	0 – 500+	10
Annual Rainfall Intensity	5	Descriptive	Very Low (<250 mm/ Yr – Very Heavy (≥ 1500 mm/Yr	10
Flooding Risk	3	Descriptive	Low, Medium, High	5
General Maintenance Frequency (Crack Seal/Pothole Patching)	5	Descriptive	Annual – No Maintenance Program	7

* Dynamic factors that can change range over a multi-year analysis period to calculate predicted Risk Factor.

The weight distributions presented in Table 1 indicate that the overall pavement performance (PQI, or a similar condition predictor) carries the highest weight (25%), indicating that the modeled future condition of the pavement is the single most influential factor in failure likelihood. This acknowledges that if a segment is projected to be in poor condition soon, it has a high probability of functional failure. Several other factors carry a weight of 10%, reflecting significant contributions to deterioration risk: for example, Age (older pavements are more likely to fail), Freeze-Thaw Cycles (harsh winters accelerate damage), Subgrade Conditions (poor underlying soil support can lead to failures), Traffic Loading (ESAL), and Annual Rainfall (heavy precipitation can weaken pavements and subgrades).

The following section describes in more detail how each of the identified PoF factors influences the probability of failure.

Age Since New or Last Reconstruction: Pavement age is a primary indicator of accumulated deterioration and fatigue. As pavements get older, materials lose elasticity, oxidation increases, and cracking becomes more likely. Therefore, increasing age generally raises the probability of failure, especially if maintenance has been inconsistent.

Pavement overall performance (Pavement Quality Index): PQI is a representation of the pavement's overall condition including the surface condition, ride quality and structural adequacy. Lower PQI values indicate more distress (cracking, rutting, potholes, etc.) and/or low ride quality, which signal higher failure likelihood. Pavement condition is often the most influential PoF factor. A declining PCI sharply increases risk if not addressed promptly.

Annual Freeze/Thaw Cycles: Frequent freeze/thaw cycles accelerate pavement deterioration by expanding and contracting trapped moisture. This mechanism is particularly severe when moisture-susceptible soils are present. This movement leads to cracking, weakening of layers, and eventually a structural damage. Regions with high cycle counts experience faster degradation rates. As a result, more cycles significantly increase the probability of premature failure.

Material Quality & Structural Design: The use of high-quality construction materials in combination with an appropriately designed pavement structure is a fundamental requirement for successful new construction and reconstruction projects. Low-quality materials, e.g., poor-quality aggregates or inappropriate asphalt binder grades, and under-designed pavement structures, for example those resulting from funding constraints that lead to insufficient layer thickness, can compromise structural integrity and reduce service performance. Such deficiencies introduce inherent weaknesses that increase the Probability of Failure (PoF). Conversely, the use of sound materials together with an adequate structural design enhances the overall pavement quality and reduces the likelihood of failure.

Construction Quality / Workmanship: Even when high-quality materials and an adequate structural design are specified, construction practices and contractor workmanship play a critical role in ensuring that the pavement structure is built as intended. Deficiencies in construction quality, e.g., inadequate compaction or inconsistencies in layer thickness, can introduce defects that accelerate deterioration and lead to premature failures. High-quality workmanship ensures that design assumptions are realized in the field, whereas poor workmanship significantly increases the probability of premature pavement failure.

Subgrade Conditions: The strength and stability of the in-situ subgrade have a direct influence on pavement performance. Weak, expansive, or moisture-susceptible soils can lead to settlement, cracking, and permanent deformation, thereby compromising structural capacity and increasing the Probability of Failure. Even when site-specific mitigation measures are implemented to address deficient subgrade conditions, the residual risk of subgrade-related failures should still be accounted for.

Daily ESAL Traffic Loading: Equivalent Single Axle Loads (ESALs) represent cumulative traffic loading including the effect of commercial traffic. Higher ESALs accelerate fatigue damage and structural wear. Heavy truck traffic is especially impactful. As traffic loading increases beyond design assumptions, the probability of failure rises significantly.

Annual Rainfall Intensity: High rainfall intensity contributes to moisture infiltration, weakening of pavement layers and subgrade support. Water accelerates stripping, erosion, and cracking propagation. Combined with poor drainage, this factor can considerably increase the likelihood of pavement failure.

Flooding Risk: Flooding exposes pavements to prolonged saturation and hydraulic forces, which can wash out supporting materials. Repeated flooding events drastically weaken the structural integrity pf the pavement structure. Even well-designed pavements can fail prematurely under such conditions. High flooding risk is a major contributor to elevated PoF.

Maintenance Frequency: Regular general maintenance (e.g., crack sealing, patching) and preventive maintenance (e.g., Slurry Seal, Microsurface) slow deterioration and extends service life. Infrequent maintenance allows minor distresses to evolve into major failures. Preventive care is critical in controlling the PoF. Lower maintenance frequency leads to a much higher probability of failure.

Consequence of Failure (CoF) Factors and Weights

CoF represents the severity of impact or consequence if a pavement section were to fail or drop to a very poor condition. Ten factors were chosen to capture the multi-faceted consequences, and their weights (summing to 100%) are listed in Table 2. These factors range from direct safety impacts to broader economic and social effects. Higher weights were assigned to factors deemed more critical by stakeholders and industry practices (with safety and mobility impacts naturally at the forefront).

Table 2. RoadMatrix™ Consequences of Failure (CoF) Factors and Associated Weights

CoF Factor	# of Categories	Data Type	Value Range	Weight (%)
Safety Hazards	5	Numerical*	0 – 20,000 vehicles/day	20
Impact on Traffic Flow	5	Descriptive	Very Low (Local) – Severe (Hwy)	15
Economic Costs	5	Numerical*	PQI-based (0 – 100)	10
Public Perception and Reputation	5	Numerical*	PQI-based (0 – 100)	5
Emergency Response Impact	5	Descriptive	No Emergency Routes – All Types of Routes (hospital/fire/evacuation/police)	15
Environmental Impact	5	Numerical*	PQI-based (0 – 100)	5
Disruption to Commerce	5	Descriptive	Very Low (Local) – Severe (Hwy)	10
Increased Vehicle Operating Costs	5	Numerical*	PCI-based (0 – 100)	5
Pedestrian and Cyclists Risks	11	Descriptive	Extremely Low (No sidewalk + No Bike Lanes) – Extremely High (Sidewalk + Bike Lane + Very High AADT (> 20,000 vpd)	10
Cost of Litigation	5	Descriptive	Very Low Likelihood - Very High Likelihood	5

* Dynamic factors that can change range over a multi-year analysis period to calculate predicted Risk Factor.

The weight distributions presented in Table 2 indicate that Safety Hazards unsurprisingly carries the highest weight at 20%. This factor is directly influenced by the number of road users, represented by the Average Annual Daily Traffic (AADT) traffic count. More vehicles on the road increases the potential for crashes or injuries associated with pavement failures. The following section describes in more detail the influencing factors that affect each of the CoF factors.

Safety Hazards: Safety hazards is one of the major consequences of failure and is proportional to the amount of road users, represented by the AADT. Defects like potholes or rutting become more dangerous under heavy traffic volumes. The likelihood of accidents rises due to driver reactions and congestion. Thus, higher ADT significantly amplifies safety-related consequences.

Impact on Traffic Flow: Roads with higher functional importance (e.g., arterials vs. local streets) carry critical traffic flows. Failure on such roads disrupts people and goods mobility and causes widespread delays. Lower-class roads have more redundancy and less impact.

Economic Costs: Allowing the overall pavement condition (represented by PQI) to drop below preventive maintenance thresholds leads to rapid deterioration. This shifts treatment needs from low-cost preservation to expensive rehabilitation or reconstruction. The cost difference can be substantial. Thus, lower PCI significantly increases long-term financial consequences.

Public Perception and Reputation: Poor pavement conditions (represented by PQI) negatively affect how the public perceives infrastructure management. Frequent complaints and visible deterioration reduce trust in the road authority. Maintaining a decent pavement condition supports a positive reputation.

Emergency Response Impact: Roads that serve as emergency route (e.g., police, fire, evacuation, and/or hospital route) are critical to maintaining timely emergency response. Pavement failure on these routes can delay or impede emergency vehicles, adversely affecting public safety and life-saving operations. Consequently, the consequences of failure are significantly greater on roads designated as emergency response routes, particularly those serving multiple emergency functions

Environmental Impact: Pavements that are allowed to deteriorate to poor overall condition (as reflected by PQI) often require more intensive rehabilitation measures, such as full-depth reconstruction. These heavy rehabilitation treatments are associated with increased material consumption, higher energy use, and greater emissions resulting from material production, hauling, and other construction activities. In contrast, timely preventive maintenance interventions have a substantially smaller environmental footprint by extending service life and reducing the need for resource-intensive treatments.

Disruption to Commerce: Higher-class roads (arterials, highways) support economic activity and goods movement. Failures on these roads disrupt supply chains and business operations. Local roads have less economic impact. Thus, higher functional class leads to greater economic consequences when failure occurs.

Increased Vehicle Operating Costs: Rough and deteriorated pavements increase fuel consumption, accelerate tire wear, and contribute to vehicle damage. In addition to travel delays, road users incur higher vehicle maintenance and operating costs under such conditions. Pavements that provide a smoother ride and maintain good overall condition help minimize these user costs.

Pedestrians and Cyclists Risks: Pedestrians and cyclists are inherently more vulnerable when using sidewalks, shared facilities, and bicycle lanes. The level of risk increases as traffic volumes rise, due to greater interaction between motor vehicles and non-motorized users. Accordingly, this CoF factor is influenced by the presence of sidewalks and bicycle lanes, as well as by traffic intensity. Risk is elevated when both pedestrian and cycling facilities are present and is further amplified on roads with high Average Daily Traffic (ADT), where increased exposure to high-volume traffic compounds safety concerns.

Cost of Litigation: Pavement failures can result in accidents, injuries, and property damage, potentially leading to legal claims against the roadway owner. The likelihood and magnitude of litigation vary by jurisdiction and regional practices and can be selected by RoadMatrix™ users to reflect local conditions.

RoadMatrix™ Risk Score Calculation and Normalization

Risk Factor in RoadMatrix™ is calculated simply by multiplying the Probability of Failure total score by the Consequence of Failure total score as illustrated in the equation below. The "Total" score encompasses the ten (10) PoF and the ten (10) CoF aforementioned factors.

$$Risk\ Factor = \ PoF\ Total\ Score\ \times\ CoF\ Total\ Score \times 100\%$$

The following equation and subsequent explanation show the mathematical formulae used within RoadMatrix™ to calculate the Risk Factor.

$$Risk\ Factor = \left(\sum_{i=1}^{n} A_i\, B_i\right) \times \left(\sum_{i=1}^{n} C_i D_i\right) \times 100\%$$

where,

$n = the\ 10\ LoF\ and\ 10\ CoF\ factors$
$A: normalized\ score - PoF factor\ (See\ A_i(c)\ equation\ below)$
$B: Assigned\ weight -\ PoF\ factor\ (Table\ 1)$
$C: normalized\ score\ -\ CoF\ factor$
$D: Assigned\ Weight -\ CoF\ factor$ (Table 2)

$$A_i = \frac{S_{i,j}}{\sum_{k=1}^{j} S_i}$$

where,

$A_i = normalized\ score -\ PoF\ factor\ i$
$S_{i,j} = scale\ factor\ corresponding\ to\ PoF\ factor\ i\ and\ selected\ category\ j$
$\sum_{k=1}^{j} S_i = sum\ of\ scale\ factors\ corresponding\ to\ PoF\ factor\ i\ and\ associated\ categories\ j$

PoF and CoF Normalization Approach

Rather than normalizing the PoF and CoF factors by the number of categories within each factor (reasonable for factors with equally-spaced risk scale), the normalization was performed using each factor's maximum scale value. This approach was adopted because several PoF and CoF factors use

non-linear scale factors to better reflect engineering principles. Normalizing by the maximum scale ensures that all factors are constrained within a 0–1 range and provides consistency across PoF and CoF factors, despite differences in the number of categories and scale structures.

All calculations are automated within the RoadMatrix™ PMS using a set of default data developed and tested as part of this work. RoadMatrix™ also provides users with the flexibility to customize both the weights and the scale factors associated with each PoF and CoF factor.

Risk Levels and Action Triggers

The continuous 0–100 Risk Score is mapped into five discrete Risk Levels which are used as a guidance to the action category. The Risk Levels are defined by Risk score ranges and each level is associated with a recommended action or management response. Table 3 presents the Risk Level classification schema and the corresponding action category.

Table 3. Risk Level Classification and General Recommended Actions

Risk Score Range	Risk Rating	Action Category
Risk < 20	Very Low	Routine Monitoring.
20 ≤ Risk < 40	Low	Low - Priority, Possibly Deferred Maintenance.
40 ≤ Risk 60	Moderate	Regular Maintenance Scheduling.
60 ≤ Risk < 80	Significant	Prioritize for M&R.
80 ≤ Risk ≤ 100	Extreme	Immediate Attention or Possibly Asset Replacement may be Required.

This classification translates the numeric risk into actionable categories easily understood by decision-makers. Very Low risk segments (scores below 20) can be safely left to routine monitoring, meaning they are in good shape, with little chance of failure and minimal impact even if distresses occur. These are often newer pavements on low-impact roads. Low risk (20–40) suggests that only minimal maintenance may be needed; these projects are candidates for deferral if budgets are tight, since the risk posed by deferring them is acceptably low. Sections with Moderate risk (40–60) indicate a need for regular scheduling in the agency's M&R plan. These segments shouldn't be ignored, but they can likely wait for their turn in the normal prioritization queue (e.g., include in the 5-year plan). Significant risk (60–80) flags segments that deserve priority attention for M&R. These sections would move near the front of the line in capital planning, as their combination of deterioration likelihood and impact is worrying. Finally, an Extreme risk classification (80–100) is reserved for the worst-case scenarios which describe segments that are so critical and so likely to fail that they require immediate intervention. In practice, an Extreme risk segment might prompt emergency repairs or an immediate project inclusion in the next funding cycle. In some cases, it could even indicate the need to consider full reconstruction or replacement if the asset is beyond repair and failure consequences are catastrophic (for example, a heavily traveled bridge or tunnel at risk of collapse would be an extreme risk scenario demanding urgent replacement).

By design, the five risk levels reflect widely used risk-matrix conventions in infrastructure management (Very Low through Extreme), converting a continuous score into categories that are easier to interpret, communicate, and tie to action. For example, it is typically more straightforward to explain that a segment is "Significant risk" and therefore targeted for rehabilitation within a defined timeframe than to communicate a pavement condition index value (e.g., PQI = 55) or a rank position (e.g., Priority 17).

The default breakpoints (20, 40, 60, 80) were initially established using our pavement experts' judgment and to broadly distribute segments across the five levels for typical networks. However, RoadMatrix™ allows agencies to calibrate these cut-offs to reflect local conditions, existing risk classification practices, and risk tolerance. For instance, if an unusually large share of segments are categorized as "Extreme Risk," the upper breakpoint can be increased to focus attention on the most critical cases. Conversely, thresholds can be lowered to encourage earlier intervention. This flexibility is supported through (1) an interface for adjusting risk-level breakpoints and (2) the ability to incorporate risk score ranges and/or specific PoF/CoF factors, quantitatively and/or descriptively, within the RoadMatrix™ decision trees (e.g., treating all Moderate-and-above segments versus limiting action to Significant/Extreme within a five-year plan, or prioritizing sections with a Risk Factor > 15 for treatments selected by the decision trees considering also performance levels and other attributes).

Integration into the RoadMatrix™ Pavement Management System

The risk-based analysis framework has been seamlessly integrated into Stantec's RoadMatrix™ Pavement Management System, enhancing its decision-making capabilities while utilizing existing data and analysis features of the system.

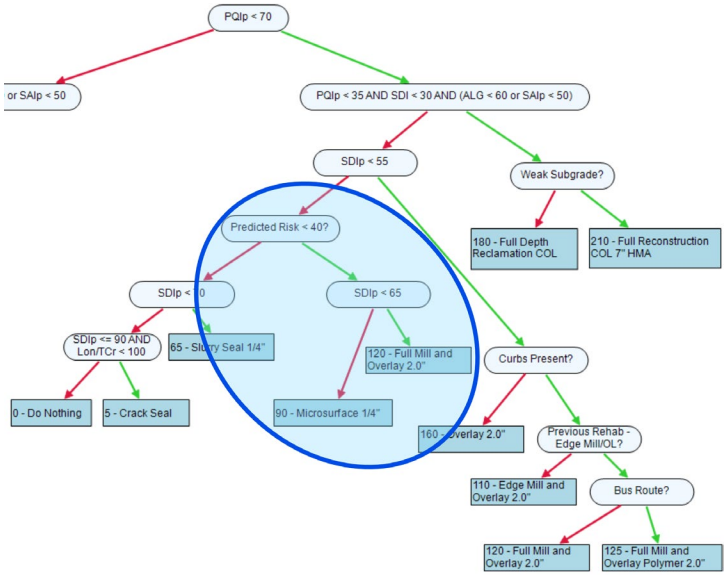
RoadMatrix™ Risk-Based Analysis Tiers

RoadMatrix offers two (2) tiers of risk-based analysis as follows:

Tier 1: This integration level calculates the current-year Risk Factor and predicts a section Risk Factor for each year in the analysis period using the system's customizable performance deterioration curves (PQI, PCI/SDI, RCI, SAI) and other inputs such as a user-defined traffic growth rate.

Predicted Risk Factor scores can be used alongside other decision-tree inputs (e.g., PQI, PCI/SDI, RCI, Functional Class, last treatment type, bus route, truck route, curbed or not, etc.) to guide treatment selection and to elevate sections whose risk may not be evident from performance indicators alone. This allows users to model M&R recommendation logic with a high degree of accuracy following the agency's current practice. Figure 1 illustrates an example decision tree in which Risk Factor (see circled risk logic) was incorporated to modify the rules such that a treatment is recommended whenever the predicted Risk Factor exceeds 40. Without incorporating Risk, the circled logic would not have been needed.

Figure 1. Example of Using Predicted Risk Factor in Decision Trees



Tier2: This highest level of integration allows for M&R analysis to be completed using the current and predicted risk and customizable decision trees and one or combination of the following analysis types:

- Achieve a specific Risk Target: The risk target can be defined to be uniform across the analysis period or different for each year of the analysis period. Users set a Risk Factor target and RoadMatrix™ will generate a recommended work program and associated cost to achieve the Risk Target. Example: for an agency with a network average current year Risk Factor of 15, the analysis could be: “Achieve a Network Average Risk Factor of 5 over the next 5 years and hold”. Users define target Risk Factor for each year of the analysis and select “Lane-Length-Weighted Risk” under the analysis type field.

- Budget based with Max Allowable Risk: Users define the maximum allowable Risk Factor for each combination of pavement type and functional class. Users then define their annual budget for each year of the analysis and RoadMatrix™ will generate a recommended work program that first targets the sections that have exceeded the max allowable Risk Factor based on their functional class and pavement type before moving to selecting sections based on cost effectiveness for any remaining funding. Users define available budget, select “Budget Limits” as the analysis type, and set the “Apply Max Risk” = “Yes”.

- Force Max Allowable Risk: This setup allows users to run a budget-based, performance-based, or risk-based analysis alongside forcing the maximum allowable risk (pre-defined for each functional class and pavement type combination) by setting up “Force Max Risk” = “Yes”. Forcing the “Max Risk” gives permission for RoadMatrix™ to exceed the defined budget, target PQI, PCI/SDI, RCI performance, or target Risk Factor to making sure that all sections that have exceeded their Max Allowable Risk Targets will be recommended for work based on the decision trees setup.

- Risk-based analysis can also be setup with any of the main analysis types (Budget Limits, Weighted Performance or Deficiency) and at the same time define other pre-defined performance goals. Users can activate the “Apply PQI Min” with and without “Force PQI Min“,

"Apply PCI/SDI Min" with or without "Force PCI/SDI Min", "Apply RCI Min" with or without "Force RCI Min" with any of the three main analysis types (Budget Limits, Deficiency Target, Weighted PQI or PCI/SDI or RCI or weighted Risk Factor.

The aforementioned analysis types give a great flexibility allowing agencies to target very specific performance, risk and budget goals.

Figure 2 below is a screen capture from RoadMatrix™ that shows an example of the various analysis scenarios that can be analyzed.

Figure 2. Examples of Setting Up Risk and Performance-Based Analysis Scenarios

Code	Fdesc	Type	Apply Max Risk?	Max Risk Forced?	Apply PQI Min?	PQI Min Forced?	Apply PCI Min?	PCI Min Forced?	Apply RCI Min?	RCI Min Forced?	2026	2027	2028	2029	2030
52	$7.0M/Year + Max Risk Forced	Budget Limits	Yes	Yes							7,000,000	7,000,000	7,000,000	7,000,000	7,000,000
50	$7.0M/Year + Max Risk	Budget Limits	Yes								7,000,000	7,000,000	7,000,000	7,000,000	7,000,000
48	Achieve a Risk of 10 over 5 years and hold	Lane-Length-Weighted Risk									16	15	13	12	10
47	Maintain 2025 Risk Score at 17.5 + Max Risk	Lane-Length-Weighted Risk	Yes	Yes							17.5	17.5	17.5	17.5	17.5
46	Maintain 2025 Risk Score at 17.5 + Max Risk	Lane-Length-Weighted Risk	Yes								17.5	17.5	17.5	17.5	17.5
45	Maintain 2025 Risk Score at 17.5	Lane-Length-Weighted Risk									17.5	17.5	17.5	17.5	17.5
44	$3.5M/Year + Max Risk Forced	Budget Limits	Yes	Yes							3,500,000	3,500,000	3,500,000	3,500,000	3,500,000
39	Avg PCI = 60 + PQI Min Forced	Lane-Length-Weighted PCI			Yes	Yes					60	60	60	60	60
38	Avg PCI = 60 + PQI Min	Lane-Length-Weighted PCI			Yes						60	60	60	60	60
36	Avg RCI = 60 + RCI Min Forced	Lane-Length-Weighted RCI							Yes	Yes	60	60	60	60	60
35	Avg RCI = 60 + RCI Min	Lane-Length-Weighted RCI							Yes		60	60	60	60	60
34	Avg RCI = 60	Lane-Length-Weighted RCI									60	60	60	60	60
31	Avg PCI = 60 + PCI Min Forced	Lane-Length-Weighted PCI					Yes	Yes			60	60	60	60	60
30	Avg PCI = 60 + PCI Min	Lane-Length-Weighted PCI					Yes				60	60	60	60	60

In addition, the RoadMatrix™ PMS interface has been updated to display Risk Scores and Risk Levels for each segment alongside condition metrics. Planners can visualize the network on a map with color-coded risk levels, quickly identifying "hot spots" of Extreme or Significant risk.
One of the strengths of integrating the Risk module into the PMS is that it leverages existing data flows and models. For instance, the predicted PQI (condition forecast) comes from the PMS's deterioration models, and is automatically updated as those models are refined.

Risk-Based Analysis Application Example

To demonstrate the RoadMatrix™ module's practical application and results, the following three (3) analysis types were performed and summarized:

- Year 1 network-level program comparison of risk-based versus performance-based budget selection logic (same annual budget; first year of analysis).
- Section-level selection comparison illustrating why specific segments are selected under the risk-based approach versus the performance-based approach.
- Network-level performance forecasting comparison showing differences in predicted PQI trends over the analysis period for risk-based versus performance-based programs.

Year 1 Program Comparison (Network-Level)

Table 4 summarizes the year-1 (2026) outcomes for two alternative program-selection logics in RoadMatrix™ under the same annual budget constraint ($3.5M). Although both analyses fully expend the available budget, they produce different programs and network effects.

Table 4. Risk-Based vs. Performance-Based Analysis ($3.5M – 2026)

Analysis Type	Budget Available	Total Spent	# of Sections Selected	LL-Weighted PQI Before Treatment	LL-Weighted PQI After Treatment	LL-Weighted Risk Before Treatment	LL-Weighted Risk After Treatment	Reduction in Risk
Performance	$3.5M	$3.5M	29	49.6	83.1	23.3	12.3	47%
Risk	$3.5M	$3.5M	11	26.4	91.2	41.2	15.6	62%

The following observations can be made based on the 2026 analysis results in Table 4:

- For the same level of funding ($3.5M), the performance-based analysis selects a greater number of pavement sections (29 sections compared to 11 sections under the risk-based analysis) with a higher average network PQI (49.6). This indicates that the performance-based approach prioritizes keeping pavements that are already in relatively good condition in good condition, and therefore selects a larger number of sections suitable for preventive maintenance and other light rehabilitation treatments.
- The observation above explains why the post-treatment average PQI achieved under the performance-based analysis is lower than that of the risk-based analysis. Preventive maintenance and light rehabilitation treatments typically provide more modest condition improvements compared to heavier rehabilitation treatments, which were predominantly applied to the 11 sections selected under the risk-based analysis. The low initial PQI score of the 11 sections was a major factor why these sections had a higher average Risk factor to start.

- The primary objective of the risk-based analysis is risk reduction, and as a result, it selects pavement sections with higher overall risk even if those sections do not achieve the highest cost effectiveness under a performance-based framework. This explains why only 11 projects were selected. These projects were deferred under the performance-based scenario due to their poor condition (average PQI of 26.4) and relatively low-cost effectiveness within the constrained $3.5M budget; however, they were selected because their average risk score was significantly higher (41.2) than that of the 29 sections selected under the performance-based analysis.

- As a result of this targeted selection, the risk-based analysis achieves a greater overall reduction in network risk (62% compared to 47%), demonstrating that concentrating investment on fewer, higher-risk sections can produce a more substantial reduction in total risk exposure, even if fewer pavement sections are treated.

Selection Rationale (Section-Level)

This example demonstrates how the two prioritization logics can produce different project selections under the same budget constraints. Rather than relying on network-level averages, this section examines specific road segments to illustrate why a segment may be advanced under the risk-based program (driven by elevated Probability of Failure and/or Consequence of Failure) while being deferred under a performance-based program (driven by relative cost-effectiveness and preservation-focused priorities). A third, “intermediate” segment is also presented to show where the two approaches converge. Collectively, the examples improve transparency by linking each selection outcome to

differences in pre-treatment performance, pre-treatment Risk Score, traffic exposure and functional importance, and the underlying PoF/CoF inputs.

Table 5. Risk-Based vs. Performance-Based Road Selection Example

Attribute Description	Section Selected only in the Risk Analysis Program	Section Selected in Both, Risk and Performance Analysis Programs	Section Selected only in the Performance Analysis Program
Street Name	112th Ave	103rd Ave	Alkire St
Pre Treatment Performance (PCI)	42.8	71.2	75.6
Risk Score Before Rehab	49.5	17.9	10.5
Rehab CE	18.1	68.5	46.8
Selected Treatment in 2026	Full Depth Reclamation ART	Slurry Seal 1/4"	Crack Seal
AADT	25,474	2,673	3,415
%Commercial	5.0%	5.0%	5.0%
Functional Class Risk Impact	Major - Arterial	Very Low - Local	Moderate - Collector
Risk-Construction \ Reconstruction Year	1975	1960	1971
Risk-Structural Design Adequacy	Good Materials + Proper Structural Design	Good Materials + Proper Structural Design	Good Materials + Proper Structural Design
Risk-Evacuation Route?	No	No	No
Risk-Fire Truck Route?	Yes	No	No
Risk-Flooding Risk	Moderate Risk (FEMA Zone X (Shaded)	Low Risk Zone (FEMA Zone X (Unshaded)	Low Risk Zone (FEMA Zone X (Unshaded)
Risk-Count of Annual Freeze/Thaw Cycles	40	40	40
Risk-Hospital Route?	No	No	No
Risk-Cost of Litigation	Very High Likelihood of Litigation	Very High Likelihood of Litigation	Very High Likelihood of Litigation
Risk-General Maintenance Frequency	Annually	> 3 - 4 Years	> 2 - 3 Years
Risk-Police Response Route?	No	No	No
Risk-Sidewalk Presence?	Yes	Yes	No
Risk-Bike Lane	Yes	No	Yes
Risk-Construction Quality/Workmanship	Good	Good	Good
Risk-Annual Rainfall Intensity (in/yr)	16	16	16

The following observations can be made based on the 2026 selection results in Table 5:

- The section selected only in the risk-based analysis (112th Ave) has the lowest pre-treatment PCI (42.8) and by far the highest pre-treatment risk score (49.5), despite having the lowest

rehabilitation cost-effectiveness (CE = 18.1). This illustrates that the risk-based approach can prioritize high-risk, high-consequence sections even when they are not cost-effective.

- The section selected only in the performance-based analysis (Alkire St) exhibits the highest pre-treatment PCI (75.6) and the lowest risk score (10.5), making it well-suited for light preservation treatments (Crack Seal). This reflects the performance-based focus on maintaining good-condition pavements through cost-effective preventive maintenance.

- The section selected in both analyses (103rd Ave) represents a balanced case, with good condition (PCI = 71.2), low risk (17.9), and the highest rehabilitation cost-effectiveness (CE = 68.5). This indicates that sections with strong cost-effectiveness and acceptable risk tend to be selected regardless of the analysis approach.

- Traffic exposure and functional importance clearly distinguish the risk-only section from the other two. 112th Ave carries substantially higher AADT (25,474), is classified as a Major Arterial, serves as a fire-truck route, and is located in a moderate flooding-risk area (versus low flooding risk for the other sections). Collectively, these attributes increase the Consequence of Failure and help explain why it is prioritized under the risk-based program.

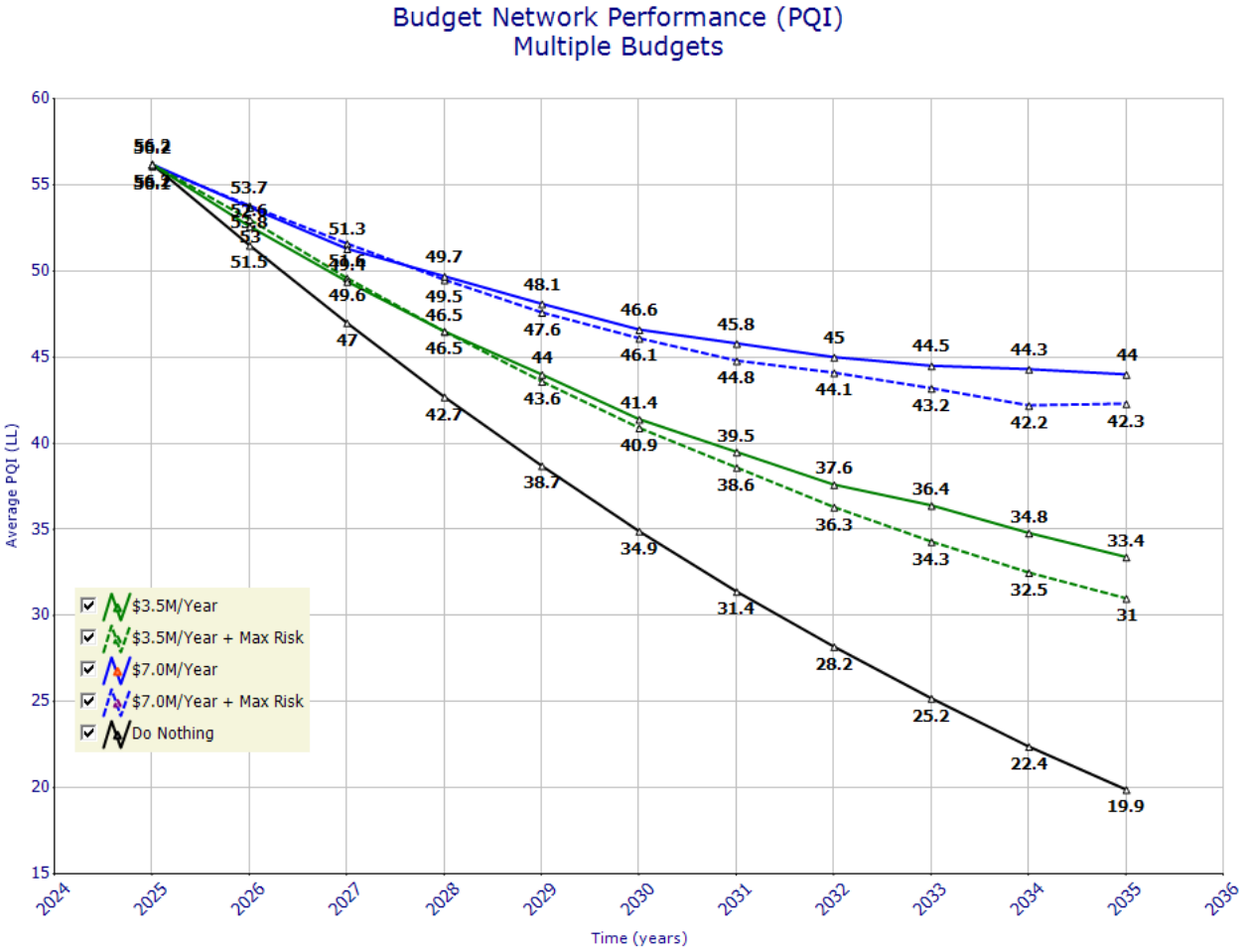
- Several inputs are effectively constant across the three sections including: construction quality, structural design adequacy, freeze/thaw exposure, rainfall intensity, litigation likelihood, as well as the absence of evacuation and hospital-route designations. This suggests that the different selection outcomes are primarily driven by pre-treatment condition and Risk Score, traffic exposure and functional classification, and relative treatment cost-effectiveness rather than environmental or construction-related factors.

Predicted Network Performance (Multi-Year)

Figure 3 from the RoadMatrix™ application compares predicted network pavement performance for risk-based and performance-based analyses under two annual budget scenarios ($3.5M/year and

$7.0M/year). For each budget level, all inputs and modeling assumptions are held constant between the two scenarios; the only difference is the program selection logic (risk-based versus performance-based).

Figure 3. Predicted Pavement Performance – Risk vs. Performance Based Analysis



The following observations can be made based on the information presented in Figure 3:

- For both funding scenarios, the risk-based analysis produces a slightly higher network PQI in the first two years; after that point, the predicted PQI falls below the performance-based results. This reflects the risk-based approach prioritizing fewer, higher-risk (often lower-PQI) sections that typically require heavier treatments—yielding larger short-term gains on treated sections but less annual coverage across the network, which reduces the long-term network-weighted average PQI.
- At the end of the analysis period shown in Figure 3, the performance-based approach maintains a higher network PQI than the risk-based approach for both budgets. For the $3.5M/year scenario, the gap is approximately 2.4 PQI points (about 33.4 vs. 31.0). For the $7.0M/year scenario, the gap narrows to approximately 1.7 PQI points, indicating that higher annual funding reduces the performance difference between the two prioritization strategies.
- The divergence between the two approaches generally increases with time (particularly under the $3.5M/year scenario), consistent with the risk-based strategy treating fewer lane-miles each year due to the higher average treatment intensity and cost per project.

- While the risk-based approach appears less efficient than the performance-based approach when evaluated using PQI alone, RoadMatrix™ does not currently quantify several key benefits of prioritizing high-risk sections (e.g., safety, user impacts, and criticality). These benefits are agency-specific and can vary significantly between network owners.

Benefits of Risk-Based Analysis

Adopting this risk-based analysis module yields several important benefits for pavement asset management:

- Improved Safety and Reliability: By prioritizing high-risk segments (which often correspond to higher accident potential or critical access routes), the agency proactively addresses the most dangerous situations. This reduces the likelihood of pavement-related incidents (like vehicle damage or crashes due to pavement surface deficiencies) and ensures critical corridors remain open and safe. In essence, the maintenance program becomes partly a safety program, targeting interventions that yield the greatest risk reduction for road users.

- The risk module helps agencies deploy constrained budgets in a way that reflects both probability of failure and consequences of failure. Instead of prioritizing projects based solely on condition or cost-effectiveness, the approach elevates segments where deterioration would have outsized impacts on safety, mobility, emergency access, or community disruption. By addressing these higher-exposure locations proactively, agencies can reduce the probability of disruptive failures and the need for unplanned interventions (e.g., emergency repairs, extended closures, and associated user impacts). In this way, risk-based prioritization complements traditional performance and cost effectiveness (CE) methods by explicitly accounting for risk tolerance and consequence, which in turn support a more balanced, defensible investment strategy over the asset lifecycle.

- Compliance and Accountability: The risk-based module directly supports compliance with federal and state\province asset management requirements that call for risk analysis in planning[10]. By quantifying risk, the agency can document how risk considerations are influencing project selection. This traceability is useful for auditors or oversight boards: each project in the M&R plan can be justified not just by condition, but by a Risk Level (e.g., “Project X is selected because it will eliminate an Extreme risk on a key route”). It also improves transparency to the public; discussions about infrastructure investment can be framed in terms of reducing risk and improving safety, which resonate well with non-technical stakeholders, and the public.

- Cross-asset and cross-disciplinary value: Introducing a consistent risk score creates a common language for discussing priorities across organizational silos. Over time, similar risk concepts can be extended to other transportation asset classes within an agency, supporting more integrated, risk-informed prioritization and trade-off discussions across programs. This approach also aligns with the direction of risk-based transportation asset management planning and reporting, helping agencies communicate more clearly with stakeholders in related functions (e.g., bridges, safety, operations, and emergency management) about why specific interventions are being advanced and what risk exposure is being reduced[11].

- Strategic planning and scenario analysis: By quantifying both current risk and forecasted risk over the analysis period, the Risk module enables agencies to establish measurable objectives for risk reduction and to evaluate trade-offs under alternative funding and policy scenarios. Users can test "what-if" questions such as the impact of a 20% budget reduction or the investment required to achieve a target network risk level within a defined timeframe. RoadMatrix™ can then quantify how much high-risk exposure remains under each scenario or how much it will cost to achieve a certain network risk level. It can also present the results in a form suitable for decision-making. Conversely, the tool can estimate the risk benefits of additional investment (e.g., the incremental funding needed to eliminate all Extreme and Significant risks). This supports a more strategic, goal-oriented planning discussion that connects pavement programming to broader agency priorities such as safety, mobility, and resilience, not solely condition metrics.

In summary, the risk-based approach makes pavement management more proactive, data-driven, and defensible. It targets the "worst risks" rather than just the "worst condition," which is a crucial distinction for maximizing public benefit from infrastructure dollars.

Limitations and Future Enhancements

While the risk-based analysis module provides a significant advancement, it is not without limitations. Understanding these limitations is important for interpreting the results and planning future enhancements:

- Data Availability and Quality: The accuracy of the Risk Score is only as good as the data behind the twenty (20) aforementioned PoF and CoF factors. Some factors (like pavement age, traffic volume, or condition) are typically well-documented. Others, such as Materials and Construction Quality or Subgrade Conditions, may not be readily available or might be qualitative. In cases of missing data, default values or subjective scores must be used, which can introduce uncertainty. Similarly, external data like climate statistics or flooding risk maps must be kept up to date.

- Subjectivity in Scoring: The factor weighting scheme and even some factor scoring involve expert judgment. For example, rating "Structural Design Adequacy" or "Emergency Response Impact" might require subjective assessment in the absence of direct metrics. This subjectivity can lead to variability. Future work could involve calibrating the scores and weights against actual outcomes from the field: for instance, after a few years, analyze whether segments that were rated high risk did indeed fail or cause issues more often than low-risk ones. This feedback can be used to adjust factor weights or scoring curves. Another idea is to incorporate machine learning techniques on historical data to fine-tune the risk model.

- Interactions and Overlap of Factors: The factors chosen, while comprehensive, are not entirely independent. For example, Age and Predicted PQI both relate to deterioration; Daily ESAL and Impact on Traffic Flow both relate to traffic usage. This means some aspects of risk might be double-counted to a degree. We tried to differentiate PoF vs CoF clearly (PoF mostly physical deterioration drivers, CoF impacts), but minor overlaps remain. There is also the possibility of interactions (e.g., high rainfall might accelerate deterioration more on roads with poor subgrade). The current model uses a simple linear combination and does not explicitly model

factor interactions. Future enhancement could explore more complex models where interactions are considered.

- Threshold effects: Grouping a continuous 0–100 Risk Score into five discrete Risk Levels is useful for communication and decision-making, but it introduces boundary effects. For example, a segment with a Risk Score of 59 is classified as "Moderate," while a score of 61 is classified as "Significant," even though the underlying risk is nearly identical. In a rule-based workflow, this can result in similar segments receiving different recommended treatments simply because one crosses a threshold. RoadMatrix™ mitigates this by enabling agencies to use the thresholds as guidance rather than rigid cut-offs—for example, by configuring decision trees with risk score bands (ranges) that are consulted automatically when generating treatment recommendations.

- Validation and acceptance: Implementing a new analysis paradigm requires validation and deliberate change management. Agency staff and leadership may need training to interpret the risk metrics, understand trade-offs, and build confidence in risk-informed recommendations. Pilot implementations are encouraged to compare risk-informed programs against historical decisions and, where feasible, observed outcomes (e.g., whether untreated high-risk sections subsequently experienced accelerated deterioration or operational issues, and whether early interventions prevented failures). Documenting these results will support continuous refinement of the approach. In addition, agencies will need to ensure that risk-module recommendations can be reconciled with other organizational priorities and constraints (e.g., political considerations, equity objectives, coordination with other capital works), which may not be explicitly represented by the current risk factors.

- Quantifying unmeasured benefits: Additional research is needed to quantify and incorporate benefits of risk-based programs that are not directly reflected in traditional condition metrics (e.g., safety improvements, reduced user impacts, environmental benefits, and improved network resilience). These benefits can vary substantially by region and by infrastructure owner, and they are therefore not currently captured explicitly within RoadMatrix™. As a result, individual agencies may need to assess and monetize (or otherwise weight) these benefits locally to fully evaluate the trade-offs between risk-based and performance-based programs.

Conclusions and Future Plans

Conclusions

This paper presented a risk-based analysis module designed to enhance pavement maintenance and rehabilitation (M&R) planning by using a composite Risk Score to trigger M&R actions. The module leverages a structured set of ten Probability of Failure factors and ten Consequence of Failure factors, each with defined weights, to evaluate the risk associated with pavement segments. We demonstrated how the 0–100 Risk Score is translated into qualitative Risk Levels ranging from Very Low to Extreme, providing clear guidance on whether a given road segment can be safely monitored or needs urgent repair. Integrating this module into the RoadMatrix™ Pavement Management System allows agencies to move beyond the limitations of condition-only prioritization and incorporate safety, traffic, and economic considerations in a transparent, quantitative manner.

The risk-based approach aligns with contemporary asset management mandates and industry best practices in risk management. By identifying high-risk assets before they fail, the module helps agencies

prevent incidents and allocate maintenance funds more effectively, thereby extending the life of assets and improving service to the public. The example scenario illustrated that a risk score can reorder priorities in a way that may better reflect community impacts than a condition ranking alone.

Key contributions of this work include the development of a practically implementable risk scoring framework, the successful integration into a live PMS environment, and the demonstration of turning risk analysis results into actionable maintenance programs. Agencies using the module gain a powerful decision-support tool to justify and optimize their M&R plans. Perhaps most importantly, this approach increases confidence that scarce resources are applied where they reduce the most risk, supporting agency goals of safety, reliability, and accountability.

Future Plans

As we advance, the intent is to continuously refine this risk-based module while keeping the implementation practical and defensible for agencies. In the short term, improvements will focus on enhancing data inputs. For example, calibrating the default Probability of Failure (PoF) and Consequence of Failure (CoF) model weights using actual data obtained from various agencies who like to participate in the enhancement. A related near-term priority is to develop regional standard lists of selectable options for the descriptive (qualitative) PoF and CoF factors listed in Table 1 and Table 2 (e.g., structural design adequacy, construction quality/workmanship, subgrade conditions, flooding risk, emergency response impact, and litigation likelihood). This would provide consistent defaults while preserving agency flexibility to tailor assumptions to local conditions and risk tolerance.

Future work will also focus on quantifying benefits of risk-based prioritization that are not captured by traditional condition metrics, enabling more consistent comparisons between risk-based and performance-based programs. This includes developing a defensible framework to estimate and report outcomes such as avoided incidents, reduced user delay and detour impacts, improved reliability and resilience on critical corridors, and other agency-defined community or environmental benefits. Where feasible, these outcomes would be monetized; where monetization is not practical, they would be represented using standardized scoring and weighting aligned with agency policy objectives. Incorporating these benefit measures into RoadMatrix™ reporting and scenario analysis would strengthen business-case justification, improve transparency to stakeholders, and better demonstrate the value of risk-informed M&R decision-making beyond changes in condition indices alone. The success of this enhancement will depend on the availability of supporting data from client networks and/or other study participants to validate assumptions and calibrate benefit estimates.

The development of this risk-based M&R work program module represents a significant step toward pavement management that is not only condition-driven but also risk-informed; continued collaboration and knowledge sharing across agencies will support refinement of the default weights and the regional qualitative option sets, helping ensure that pavement management decisions remain transparent, comparable, and resilient over time.