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# GIS-based risk management database integration and implementation framework for transportation agencies

by

**Inya Nlenanya**

A dissertation submitted to the graduate faculty

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DOCTOR OF PHILOSOPHY

Major:  Civil Engineering (Transportation Engineering)

Program of Study Committee:
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Heike Hofmann
Kristen Cetin

The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this dissertation. The Graduate College will ensure this dissertation is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University

Ames, Iowa

2019

# DEDICATION

To my family and to those who told me to build a shelter wherever

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# ACKNOWLEDGEMENTS

This has been quite the journey. Thanks to Dr. Konstantina “Nadia” Gkritza for getting the ball rolling again.

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# ABSTRACT

Risk management analysis is one of the new requirements under MAP-21 and subsequently the FAST Act that separates transportation asset management programs (TAMP) from business as usual for the State departments of transportation (DOTs). Based on this requirement, each agency will discuss the concept of risk and how it should be incorporated into its transportation asset management program as well as how it informs maintenance practices, asset replacement or rehabilitation, and emergency management and response planning. This will require an agency to provide a list of risk exposures and document its system-wide risk management strategy.

As a result, this research investigates the state of the practice of how agencies are developing their risk-based asset management plan and discusses recommendations for future research. The survey results show that state highway agencies are increasingly adapting the way they do business to include explicit considerations of risks. At the moment, this consideration of risk is not linked to data, and as a result most agencies do not have a data driven way of tracking risks and updating their risk exposures. Accordingly, this research proposed a data integration framework utilizing Geographic Information Systems (GIS) and Application Programming Interface (API) to implement a risk management database of all the relevant variables an agency needs for risk modeling to drive risk mitigation, risk monitoring, risk updates, and decision making. In addition, this study proposed modifications to the risk register workshop that leverages the collaborative aspects of risk management to quantify risk in monetary terms.

This study leverages available data and analysis tools to help agencies visualize and articulate, in both qualitative and quantitative terms, how the combination of various risks and strategies would influence performance targets. The significance of the results highlights the need for further research on data driven risk management and to synthesize methodologies for integrating risk assessment into the agency’s decision-making process.

# CHAPTER 1. GENERAL INTRODUCTION

## Background

Since the majority of the Eisenhower Interstate Highway System was completed in the 1980s, investment and innovation in the U.S. transportation infrastructure—roads and bridges, airports, public transit, and railway systems—have trailed other leading world economies even though traffic volumes, weight of freight, and legal truck weight limits have all changed considerably (1). As a key source of revenue, the federal fuel tax was last raised in 1993 (2) and since it is not indexed to inflation, it has experienced a cumulative loss in purchasing power of 74.4 percent between 1993 and 2018 (3). In addition, fuel efficiency has doubled between 1974 and 2003 putting a squeeze on this funding mechanism for US infrastructure (1). To put it in perspective, Americans are driving two times as many miles per gallon (4), hence while revenue is dropping, traffic volume has increased worsening the congestion of US highways and putting a strain on the infrastructure (5).

In 2008, the United States Congress established the National Surface Transportation Infrastructure Financing Commission (NSTIFC) to provide recommendations for policy and action that will inform efforts towards a national surface transportation system that is more efficient, more effective, and more sustainable. The commission's report confirmed that system demands were outpacing investment in the U.S. transportation infrastructure as well as the fact that system maintenance was competing with the necessary expansion of the system (6). In the report, the commission's estimates of surface transportation investment needs with baseline revenue projections showed a federal highway and transit funding deficit of nearly $400 billion in 2010-15 and projected to hit $2.3 trillion through 2035. As a result, among the recommendations made by the commission in response to its charge was the proposal of a national asset management program that will keep the nation's infrastructure in a state of good repair and increase system reliability (7).

## Asset Management Timeline

Asset management, although not a new concept, is a practice that is growing in the transportation industry (8). The beginning of asset management application by a transportation agency can be traced back to the American Association of State Highway Officials' (AASHO) Road Tests conducted in the late 1950s to determine the relationship between structural designs and expected loading over pavement life (9). The results of this study led to the development of performance measures and the ability to forecast pavement condition and, eventually, pavement management systems (PMS). Two decades later, bridge management programs in the United States began in response to Federal legislation after the collapse of the Silver Bridge, between Ohio and West Virginia, in 1967 (9). Today, state transportation agencies have established pavement and bridge inspection programs and most have made significant progress in the implementation of PMS as well as bridge management system (BMS) which was formalized in the mid-1990s (8, 10).

In 1991, the Intermodal Surface Transportation Efficiency Act (ISTEA) was signed into law as the first U.S. federal legislation on transportation planning and policy in the post-Interstate Highway System era which shifted emphasis from highway expansion to maintenance and preservation (11). ISTEA was based on asset management principles, going as far as to mandate the establishment of six management systems- pavement, bridges, highway safety, traffic congestion, public transportation facilities and equipment, and intermodal transportation facilities and systems- a requirement that was later rescinded (9, 11, 12).

Using asset management, state departments of transportation (DOTs) have made progress in reducing the total cost of designing, acquiring, operating, maintaining, replacing, and disposing of their capital transportation assets during their useful lives while accomplishing the desired levels of service (13). According to the American Association of State Highway and Transportation Officials (AASHTO), a transportation asset management program (TAMP) is a strategic approach that focuses on a DOT’s business process for resource allocation and utilization with the objective of better decision making based on quality information and well-defined goals (14).

Following these guidelines, a well-developed asset management system must include the following: asset inventory and condition assessment, asset management objectives and measures, performance gap assessment, lifecycle cost considerations, financial plan, and investment strategies (8).

The asset inventory and condition assessment provide an overview of the assets owned by an agency, and a comprehensive description of the current conditions of those assets in terms of materials, age, components, condition rating and replacement value. Understanding what assets an agency owns and its current condition is typically the ground zero of any successful asset management plan.

Asset management objectives and measures describe the methods that an agency is using to track and manage performance and how those measures are selected to support the agency’s overall goals and objectives. If a TAMP was an optimization problem, then this component of the TAMP defines the target to maximize given the agency’s resource constraints.

Under performance gap assessment, current and future target levels of service and performance are identified for each asset. Measures of service can be in terms of condition, reliability and availability or operational parameters. It answers the question of how well the available resources can maintain the desired performance targets. It helps the agency provide a warranty on their operations.

The life cycle cost analysis (LCCA) provides more detailed information about the assets, such as condition and performance summaries, asset life cycles, useful and remaining lives. In addition, it identifies what the critical assets are and proposes condition and performance models that define the relationship between the agency's actions to improve the assets versus the costs to do so. It is obvious that when evaluating alternative maintenance objectives, assets deteriorate over time and most LCCA require some means of modeling that deterioration and the effects of maintenance actions on the rate of deterioration.

The financial plan component includes details of the funding available for TAMP activities, and how it has been programmed by asset type. This component is linked to, and reflective of the agency's capital improvement plan. The focus of this component is not just on the amount of available funding but on revenue sources and a comparison of currents needs with past condition and spending patterns.

The investment strategies of a TAMP describe the process by which an agency translates its data, objectives, measures, and policies into decisions on how to spend its limited resources. This section uses the available funding detailed in the financial plan to provide at least two scenarios: 1) projected trends toward goals using the existing funds; and 2) the required funds needed to meet all goals.

However, state DOTs tend to limit TAMP to the physical serviceability of the asset in terms of condition measures and structural sufficiency ratings for pavements and bridges respectively (14). A viable financial plan and investment strategies can only be accomplished if risk considerations are a part of the overall TAMP. To this end, on July 6, 2012, the Moving Ahead for Progress in the 21st Century Act (MAP-21) was signed into law by President Obama. It is the first long-term highway authorization passed since 2005. Like ISTEA, more than two decades prior, MAP-21 is a milestone legislation on the road towards a more efficient, more effective, and more sustainable national surface transportation infrastructure.

MAP-21 creates a streamlined, performance-based, and multimodal program to address the many challenges facing the nation’s transportation system. These challenges include improving safety, maintaining infrastructure condition, reducing traffic congestion, improving efficiency of the system and freight movement, protecting the environment, and reducing delays in project delivery (15).

Under MAP-21, performance management became an integral part of federal highway programs by providing a basis for a more efficient investment of federal transportation funds. Consequently, it focuses on national performance goals, increasing the accountability and transparency of the federal highway programs, and improving transportation investment decision making through a performance-based paradigm. This paradigm is codified in the requirement for the development of risk-based transportation asset management plans (TAMP) that includes strategies resulting in a set of programs that would make progress toward achievement of the State targets for asset condition and performance of the National Highway System (NHS). The Fixing America’s Surface Transportation Act (FAST) that was signed into law December 4, 2015, provides long-term funding certainty for surface transportation infrastructure planning and investment, which builds on the changes made by MAP-21 (16).

## Risk Management Integration

Risk management analysis is one of the new requirements under MAP-21 and subsequently FAST ACT that separates TAMP from business as usual for the State DOTs by requiring State DOTs to adopt the same business practices that are prevalent in private enterprise and international transportation agencies. Risk management is a process of analytical and management activities that focuses on identifying and responding to the inherent uncertainties of managing a complex organization and managing capital facilities (17). The International Organization for Standardization (ISO) defines risk management as the effects of uncertainty on objectives (18). Therefore, risk management is necessary to ensure that agencies are able to effectively implement their TAMP. Risk management is a cyclic process as shown in Figure 1.1 (19) and it is made up of the following components:

- **Event Identification.** Identify risk events that could impact an agency's ability to effectively manage its assets. This involves identifying and documenting all foreseeable risks and the triggers that can undermine agency goals and objectives
- **Risk Assessment.** Evaluate the likelihood of an event happening and the consequences if it were to happen. This helps an agency make the best decision by comparing the extent of a risk with the agency's risk tolerance as it relates to its programs and projects.
- **Risk Response.** Identify a plan for responding to each of the highest ranked risks by treating it or mitigating the risks to acceptable levels.
- **Control Activities.** Implement the risk response strategies identified in the risk response stage.
- **Risk Monitoring.** Monitor and respond to possible events, and evaluate the mitigation strategies to ensure that it still appropriate to the risk characteristics.

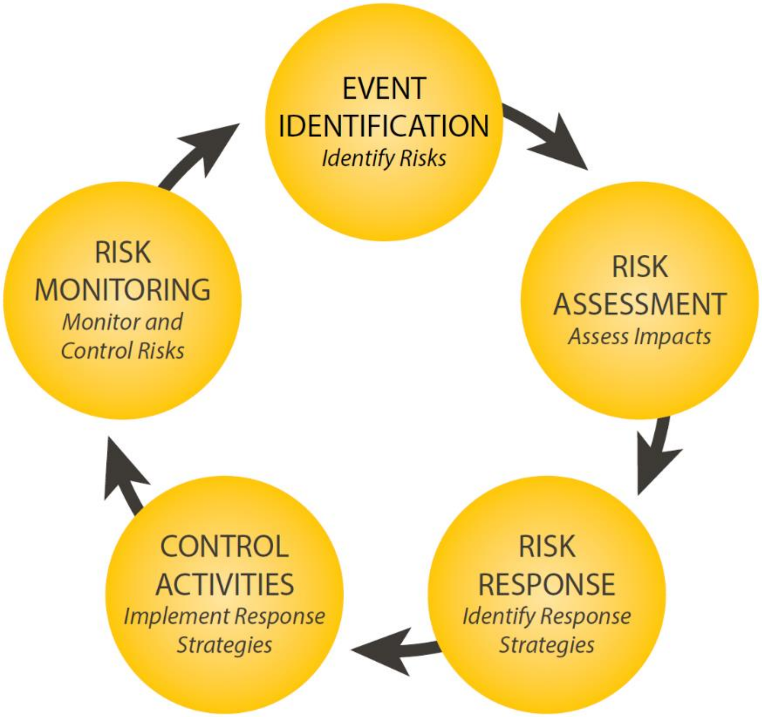

Figure 1.1 Risk Management Process (19)

Hence, a risk-based asset management approach is tasked with identification of risks that affect the DOT's capacity to meet its stated goals, assessment of the impacts of the risks as well as proffering mitigation (20). The DOT's mitigation strategies are greatly improved by an objective mechanism for measuring the identified risks, as this will help drive possible mitigation activities- ensuring that the response does not overstate or understate the risk event. The monitoring and updating of the risk management process is critical to ensure that new risks are identified, and existing risks are tracked and updated (17). To help agencies understand the impacts associated with the risks as they occur, agencies need to properly track asset failures as well as the impacts of poor data, inadequate funding, and the lack of decision support tools on their operations and planning. In addition, this would enable the agency to quantify the likelihoods of these risks. This ability to track and quantify risk would benefit the risk classification process (21) and its seamless integration into an asset management plan.

Furthermore, it will help ensure that the financial plan and investment strategy components of the TAMP are appropriate to ensure that the agency continues to fulfil its primary responsibilities.

One important aspect missing that is worth stating is how agencies intend to use risk to modify their decision-making process. However, to get to that point, there is need for a risk management framework that will help agencies transform their data collection endeavors into actionable business intelligence. This dissertation focuses on developing such a risk management framework that will provide decision makers with the ability to track risks in quantitative terms and a framework for prioritizing those risks.

## Research Objectives

The goal of asset management is the development of a decision-support framework that is integrated with quantitative data on how an organization's resources and decision-making impacts its facilities' current and future performance (11) in the face of uncertainties. In order to accomplish this, this research has the following objectives:

- To investigate the current state of the practice for integrating risk management in U.S. state highway agencies' TAMPs. In the process, synthesize inputs from state transportation departments on their TAMP readiness, risk identification process, and what available data were used to generate the risk registers, as well as future research endeavors.
- To develop a framework, that is cognizant of the qualitative and quantitative nature of risk, for a geographic information system (GIS)-enabled database appropriate for risk modelling.

- To implement the GIS-enabled risk management database fully integrated with a mechanism for estimating probability, severity, and consequences of a risk event happening based on available data.

## Research Approach

Three major tasks are conducted to fulfill the objectives of this study. Figure 1.2 shows the overall methodology and organization of the dissertation. The first objective of this research is to synthesize a state of the practice survey of all 50 state highway agencies to understand how each DOT is currently integrating risk management into their TAMP, what available data (hard data or soft data) informed the risk identification process, and what additional data were needed to properly execute the risk assessment process.

The results of this state of the practice survey along with a review of all TAMP documents submitted by state highway agencies are then used to propose the design and implementation of a GIS-enabled database for risk management as a template for driving a quantitative approach to risk assessment, tracking, and monitoring to enhance the decision-support infrastructure. As a result, the second objective covers the development of a data integration framework that would result in a GIS-enabled risk management database that is populated by integrating data across divisions and assets with external data sources that are necessary for capturing the risk characteristics of an agency.

The final and third objective is the implementation of the risk management database- a comprehensive cross-asset database of all the important data items that agencies need to successfully execute their risk-based asset management plan. This will form the basis for quantifying the relationship between risk and consequences and integrating the results in a GIS-enabled dashboard and data mining applications for visualization and data modelling.

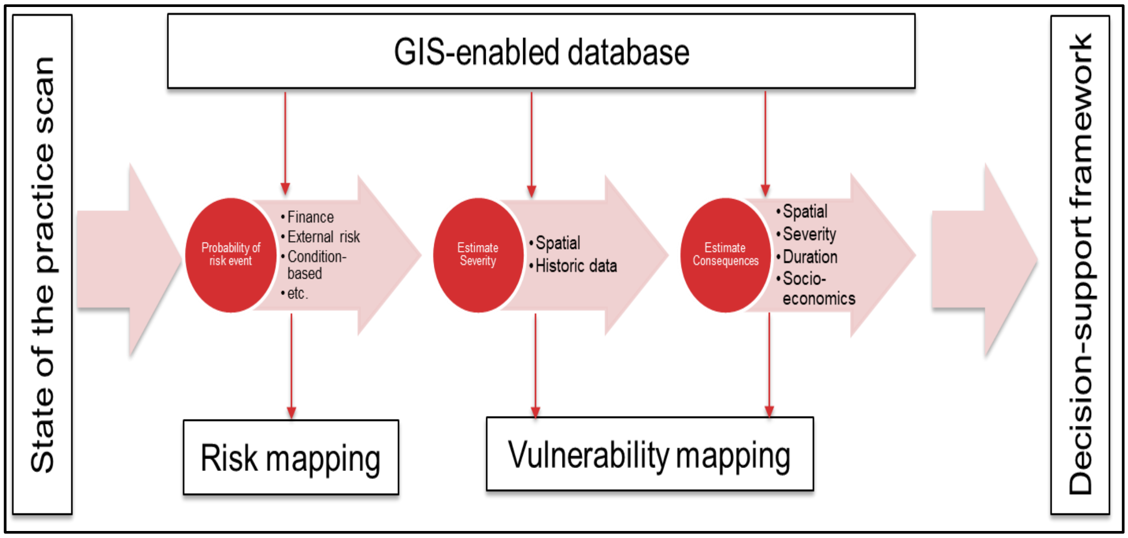

FIGURE 1.2 Research Methodology

## Dissertation Organization

This dissertation is divided into five chapters. Chapter 1 provides a general introduction that includes brief background information, dissertation objectives, dissertation organization, and expected contribution of the research.

Chapters 2-4 comprise papers that have been either published or prepared for submission to peer reviewed journals. The papers are ordered in the dissertation as follows:

Chapter 2: Risk management and data needs: a state of the practice survey of state highway agencies

This paper was presented at the 97th Transportation Research Board (TRB) Annual Meeting and published in the Transportation Research Record Vol 2672, Issue 44, 2018.

Chapter 2 presents findings from the state of the practice survey of how state highways agencies are integrating risk in their TAMPs as well as identified research needs to facilitate state DOTs compliance with the MAP-21 and FAST Act requirements. It includes a discussion of agencies' TAMP readiness, the risk identification process, and what available data were used to generate the risk registers.

Chapter 3: Database design and data integration framework for risk management by state highway agencies

Chapter 3 proposed a framework for designing and developing a risk management database by integrating all the relevant data that drives an agency's risk management process. It identified the challenges facing data integration implementation and recommended best practices for overcoming the challenges by proposing modifications to the risk identification process that is currently in place at all state highway agencies. The proposed modifications captures the qualitative and quantitative nature of risk management.

Chapter 4: Risk management database implementation framework for state highway agencies

Chapter 4 implemented the data integration framework using Iowa DOT data and risk registers to implement a risk management database. In the process, designed an API for data extraction, integration, and risk calculation. This chapter also provided guidance on how agencies can measure risk related to data collection and data modelling.

Finally, Chapter 5 summarizes the major findings of the study and includes recommendations for future work.

## Expected Contribution

The need for a model that quantifies the relationship between risk events and cost is critically needed. From the state of the practice survey, state highway agencies are taking more and more ownership of their TAMP. This is obvious in how some agencies are reorganizing their asset management groups to include a policy-focused group in charge of development and a technical group in charge of the risk management process and implementation.

Currently, the risk assessment process is driven more by a subjective process than by data that is currently tracked. This research project will build on the state of practice by developing a data integration template that will result in risk management database integrating and tracking quantitative risk measures in a GIS environment for visualization and data analytics. This effort will go a long way to help DOTs with risk assessment, mitigation and recovery strategies as well as complement efforts toward a national surface transportation system that is more efficient, more effective, and more sustainable.

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# CHAPTER 2. RISK MANAGEMENT AND DATA NEEDS: A STATE OF THE PRACTICE SURVEY OF STATE HIGHWAY AGENCIES

Modified from a paper published in the Transportation Research Record (TRB). Vol 2672, Issue 44, 2018

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## Abstract

Risk management analysis is one of the new requirements under MAP-21 that separates transportation asset management programs from business as usual for the State departments of transportation (DOTs). Based on this requirement, each agency will discuss the concept of risk and how it should be incorporated into its transportation asset management program as well as how it informs maintenance practices, asset replacement or rehabilitation, and emergency management and response planning. This will require an agency to provide a list of risk exposures and document its system-wide risk management strategy. This paper presents the results of a state of the practice survey of how agencies are developing their risk-based asset management plan and discusses recommendations for future research. The results show that state highway agencies are increasingly adapting the way they do business to include explicit considerations of risks. At the moment, this consideration of risk is not linked to data, and as a result most agencies do not have a data driven way of tracking risk and updating their risk exposures. The significance of the results highlights the need for further research on data driven risk management and to synthesize methodologies for integrating risk assessment into the agency's decision-making process.

## Introduction

On July 6, 2012, the Moving Ahead for Progress in the 21st Century Act (MAP-21) was signed into law by President Obama. MAP-21 and the Fixing America's Surface Transportation Act (FAST) which supersedes MAP-21, require states to develop and implement a risk-based asset management plan for the national highway system (NHS) to improve or preserve the condition of the assets and the performance of the system. The legislation focuses on the development of a transportation asset management program (TAMP) for bridges and pavements on the NHS, as well as other infrastructure assets within the right-of-way corridor (*1*, *2*).

Risk management analysis is one of the new requirements under MAP-21/FAST that separates TAMP from business as usual for the State departments of transportation (DOT). As a result of this requirement, each agency will discuss the concept of risk and how it has been incorporated into its TAMP as well as how it informs maintenance practices, asset replacement or rehabilitation, and emergency management and response planning. This will require an agency to provide a list of risk exposures and document its system-wide risk management strategy. The intent of this paper is to understand how each state is currently integrating risk management into their (TAMP), what available data informed the risk identification process and what additional data is needed to properly execute the risk assessment process. To accomplish this, an online survey of state DOTs was conducted to determine how risk management is being integrated. In this paper, we summarize the responses to the survey as well as discuss its implications for risk-based asset management.

## Background

Risk is defined as the positive or negative effects of uncertainty upon agency objectives (*3*). Risk is anything that minimizes one's ability to achieving stated goals and objectives. While, the entire concept of risk management is to control potential negative outcomes, in the case of positive risks, it occasionally deals in opportunity (*4*) by supporting activities that foster innovation or bringing about the greatest returns on investment (5). Hence, risk management is a process of analytical and management activities that focus on identifying and responding to the inherent uncertainties of managing a complex organization and managing capital facilities (*3, 6*). In the context of transportation agencies, it generally consists of the strategic and systematic process of operating, maintaining, and improving physical assets and managing their highway network with an emphasis on minimizing threats and maximizing opportunities. Hence, a risk-based asset management approach is tasked with identification of risks that affect the DOT’s ability to meet its stated goals, assessment of the impacts of the risks as well as proffering mitigation (*4*). At the core of this is the ability for transportation agencies to be able to have a mechanism for measuring the identified risks, as this will help drive the possible mitigation activities.

These risks are generally a result of anticipated future outcome dependent on metrics of both present conditions as well as future predictions. They cut across technology, human resources, weather and environmental conditions among other things. Colorado DOT considered, as part of their TAMP process, the following three levels of risk (*7*):

1. Agency (Strategic, Corporate) Risks – Affects mission, vision, and overall results of the asset management program. Examples include politics, public perception, reputation, levels of available revenue, etc.
2. Programmatic (Business Line) Risks – Affects DOTs ability to deliver projects and meet targets within a program. These may include organizational and systemic issues as well as revenue and economic uncertainties that in general cause project delay. These issues

can be multivariate. Examples include project delivery risks, revenue uncertainties, cost-estimating processes, revenue and inflation projection inaccuracies, construction cost variations, materials price volatility, data quality, retirements, etc.

3. Project/Asset Risks – Affects scope, cost, schedule, and quality of projects. In contrast to programmatic risks, project risks are related to specific projects. In other words, there are inherent issues in a given project that may result in a project delay. Examples include hazardous materials, geology, environmental issues, right-of-way issues, utilities, project development timeline/delays, scope growth, cost overruns, project delays, etc.

Although all the above levels of risk are clearly defined, there exists significant overlap in what an agency needs to do at every level. The identification of the actual data needed in each level for risk identification and analysis is a very challenging task. This is partly due to the substantial overlap between the various levels, as well as the lack of relevant research initiatives in this field (*8*).

Nevertheless, an astute understanding of these levels of risk is a very good starting point for risk management. The ISO Risk Management Framework (*6*) (Figure 2.1), is very helpful to breaking down the broad categories of risk into actionable pieces for the agency to tackle. They include:

1. Establish context: This means understanding what aspect the risk covers. It could be social, environmental, economic, legal, cultural, etc. This also identifies the specific policy goals or objectives that the risk undermines.
2. Identify Risk: Identify the risks to the assets with respect to the agency’s management goals. This process discloses and documents all foreseeable risks and its triggers that could affect policy goals and objectives.

3. Analyse Risk: Find out what impact this risk will have on the overall asset management plan. This process determines the likelihood and consequence of failure.

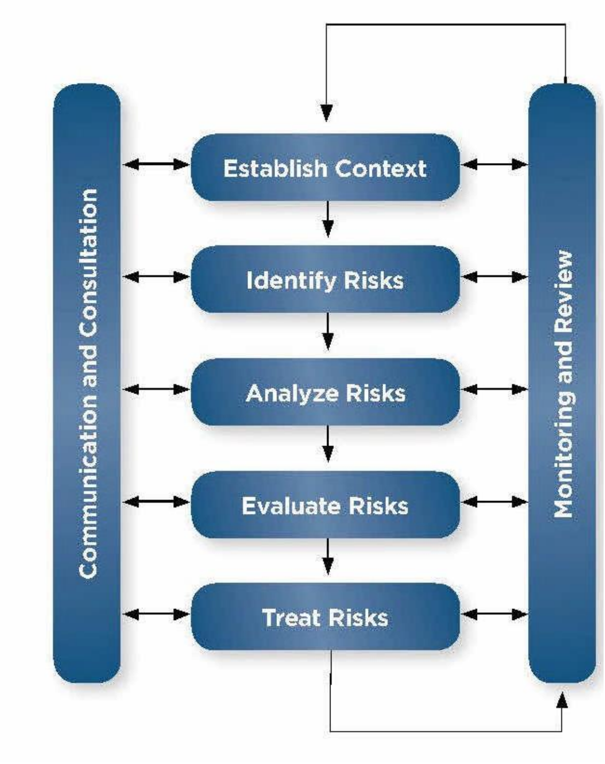


Figure 2.1 ISO Risk Management Framework (6)

4. Evaluate Risk: This stage helps to firm up decisions taken by comparing magnitude of risk with its risk tolerance based on its relative importance to the agency, program, or project.
5. Mitigate Risk: This decision-making step applies the "five Ts" which are to treat, tolerate, terminate, transfer or take advantage of the risk. This involves determining appropriate mitigation strategies as well as monitoring strategies, and re-evaluating risks.

Effective risk management is only possible if the appropriate methods, which address the root cause of the identified risk, are utilized in its mitigation. All agencies have a common goal of achieving a stated level of low risk to their assets and this will require constant communication and consultation with the affected stakeholders as well as constant monitoring and review by the agency. To this end, this research provides insights into how the agencies are integrating risk into their TAMP and provides actionable intelligence on how to further refine the process.

## Research Objectives

The primary objectives of this research were to investigate the state of the practice for integrating risk management in U.S. highway agencies' TAMP and to make recommendations for future research into bridging the resulting gaps. Findings address the TAMP readiness of the agencies, the risk identification process, and what available data were used to generate the risk registers. Objectives of this research also included the following:

- Complement the research conducted for the NCHRP 08-93: Managing Risk across the Enterprise- A Guidebook for State Departments of Transportation (9) as well as all prior studies in this area and
- Determine research needs to assist state DOT compliance with MAP-21 and FAST Act requirements.

## Results

An online survey was prepared and sent to all 50 state highway agencies to understand how each state is currently integrating risk management into their TAMP, what available data (hard data or soft data) informed the risk identification process, and what additional data is needed to properly execute the risk assessment process. The unit of the survey was the state DOT. The scope of the study was limited to the state DOTs. The survey covered three main topics: TAMP readiness, risk identification methodology, and linking risk identification and assessment to data. The questions were prepared by using various formats, such as radio buttons, check-all-that-apply boxes, ranking, and short essay question fields. The ranking questions employed randomization of the options to eliminate bias due to order. Some questions asked recipients to elaborate on their selections in essay fields or to provide supplementary information. Furthermore, the recipients were asked to provide their contact information if they were willing to permit the survey team follow up on their responses.

A total of 26 completed surveys from 50 States were received. Therefore, the response rate was 52 percent.

## TAMP Readiness

This section addresses how far along the agencies are in terms of developing their risk-based TAMP framework.

### Asset management task force

An asset management group or task force is usually the first step towards formalizing an agency’s commitment to asset management and institutionalizing TAM as a business process. More than 90 percent of the responders confirmed the existence of a task force to coordinate all of their asset management activities.  The high percentage is an improvement compared to a previous study published in 2013 (*10*). A follow up question on the composition of the task force was asked and the responses were consistent with what was reported in (*10*). The only difference is that most agencies are reorganizing and refocusing the asset management group to not only have a policy-oriented function but also include a steering committee or a technical working group tasked with implementation. The policy side is made up of division heads/administrators and unit leaders that encompass the following disciplines: bridge, pavement, planning and programming, operations, research, IT, design, materials, data management, and finance. They are responsible for developing the TAMP.

On the other hand, the steering committee or technical working groups are made up of the data owners, data managers, and an asset liaison from each of the agency's asset class to serve as a line of communication between the asset and the technical working group to help facilitate proactive asset management. The steering committee is responsible for the implementation of the TAMP. This can be evidence that more and more agencies are taking ownership of the TAMP process and reorganizing it in the best way that fits with their unique situations.

### Risk management task force

With the requirement under MAP-21/FAST for risk-based asset management, 70 percent of DOT responders have the asset management group taking the lead on the development and implementation of the risk management portion of the TAMP. This is the case since the many of the identified risks and strategies are foundational for the TAMP development. A follow up question on the composition of the risk management group was asked to see if agencies were incorporating the risk requirements as part of the overall TAMP or as an independent part. The responses showed that the reorganization of the asset management group was due to the accommodation of the risk requirements. The main reason for the technical working group was to create a more focused group working on aligning risk management with agency's overall goals.  Regardless of whether the asset management group is in charge of the risk management activities or not, most responders agree that there should be a clear line of communication between the risk management activities and the overall agency policy and goals to make sure that strategies and initiatives are in sync with responsibilities.

### Linking strategic goals to risk

From the discussion on TAMP readiness, there is obvious momentum among state highway agencies to implementing risk-based asset management. However, there is need to understand how a risk is assigned to either agency, program, or project level. Is it based on its scope or magnitude of its impact? This is important because risk management concept requires that risk be treated at its highest level (*11*). It is likely that a given risk can impact an agency at both the program and agency level. In that case, the risk should be mitigated at the agency level.

In a follow up question, one agency responded that risk identification was conducted by asset category and then sorted into the various levels of the risk management program. This undoubtedly allows the agency to upscale or downscale a risk depending on their understanding of its scope and magnitude.

In addition, it is imperative to link strategic goals to risks to ensure that risk is identified and placed at its highest level. However, 55 percent of the responders linked strategic goals to risk, just two agencies more than those that treated it independently. The small gap can be explained by the fact that some agencies were actually doing both. This was confirmed in one follow up interview.

### Risk Management Practice

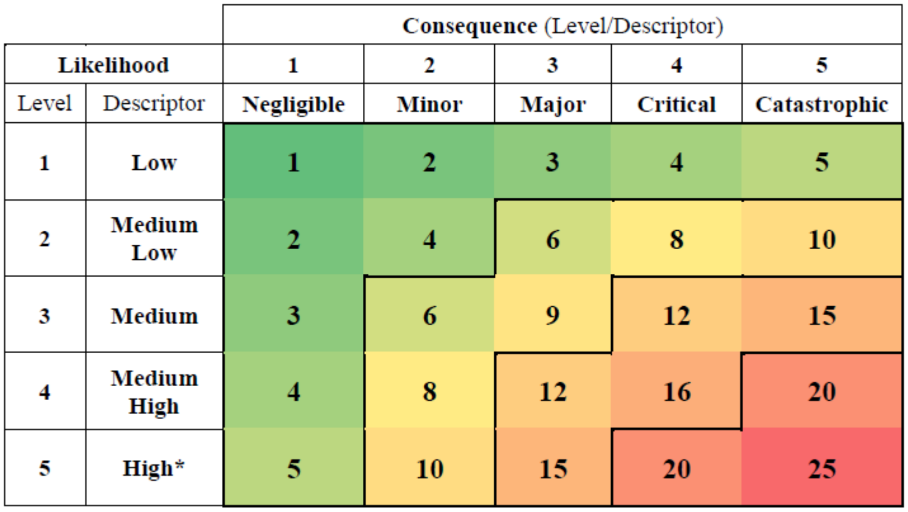
This section focuses on how state highway agencies are integrating risk into their TAMP. The application of risk-based asset management as required by MAP-21/FAST is still in its infancy (*12*, *13*). Risk management is the core principle of asset management (*6*). The product of risk management is efficiently using available resources to manage programs through improved communication. Applying risk management to look at decision-making about program delivery makes it possible to identify risk triggers, assess and prioritize those risks, and determine strategies that provide a framework on how best to deal with future issues affecting agency goals (*14*).

When asked about the methodology for the risk identification process, all the responders had a similar methodology for risk identification. Through consultation with senior management, asset managers, subject matter experts, key staff from various asset classes and in one case an outside consultant, most agencies performed strategic risk identification in workshops. From this risk identification workshop, risk registers were compiled. This confirms the findings in (*3*) that risk register is the most commonly used tool for risk management for all levels of risk. All the draft or final TAMP documents of state DOTs on the AASHTO TAM portal all utilized a risk register to execute their risk management.

The risk register was evaluated in terms of the likelihood of a risk event and impact. The scale (Figure 2.2) shows the risks identified at the workshop with their determination of the likelihood of the event occurring, where 5 is high and 1 is low. The risk was then assessed in terms of its consequence, where 5 is catastrophic and 1 is negligible.

Risk registers and their outputs such as heat maps allow definition of priority risks through risk evaluation, establishing risk tolerances and decision criteria, and using these factors to inform response/treatment. More than 90 percent of the respondents had developed risk registers that encompass both agency and program-level risks. This is consistent with what was reported in (*15*). Only 15 percent of the responders had generated risk registers for all three risk levels.

These risk registers are intended by the agencies to be a living document that is updated as new risks are encountered. Figure 2.3 summarizes the frequency of risk registers review and update. Across all survey responders, most agencies did not have a set schedule for updating the risk registers while 23 percent revise annually. Some agencies preferred to review and update as needed. This provides a more complete and updated view of state DOTs schedule for updating the risk register with 24 agencies responding than what was reported in O'Har, J.P. et al. (*15*) with only 13 state DOTs responding. Both agree that most agencies are still unsure how frequently to revise the risk registers.



| | | **Consequence** (Level/Descriptor) | | | | |
|---|---|---|---|---|---|---|
| **Likelihood** | | **1** | **2** | **3** | **4** | **5** |
| Level | Descriptor | **Negligible** | **Minor** | **Major** | **Critical** | **Catastrophic** |
| **1** | **Low** | **1** | **2** | **3** | **4** | **5** |
| **2** | **Medium Low** | **2** | **4** | **6** | **8** | **10** |
| **3** | **Medium** | **3** | **6** | **9** | **12** | **15** |
| **4** | **Medium High** | **4** | **8** | **12** | **16** | **20** |
| **5** | **High*** | **5** | **10** | **15** | **20** | **25** |

Figure 2.2 Risk Rating Scale (8)

### Risk identification and data

The purpose of this section is to understand the data that were used to drive the risk assessment process and what additional data is needed. The monitoring and updating of the risk management process is critical to ensure that new risks are identified and existing risks are tracked and updated (*3*). To help agencies understand the impacts associated with the risks as they occur, agencies need to properly track asset failures. This ability to track and quantify risk would benefit the risk classification process (*16*) and its seamless integration into TAMP. The agencies were asked about what data (hard data or subjective data) were considered in their risk assessment exercise and rank its importance. The results in Tables 2.1-2.3 for the strategic, program, and project level risks respectively, show only the factors that were consistently ranked in the top three as presented in columns 1, 2, and 3. For strategic risks, the top three driving factors for the risk assessment were historic funding levels, policy changes and political climate, and the financial market (Table 2.1). Also ranking high was upper management personnel changes. These are consistent with what would impact the success of a TAM implementation (*17*).

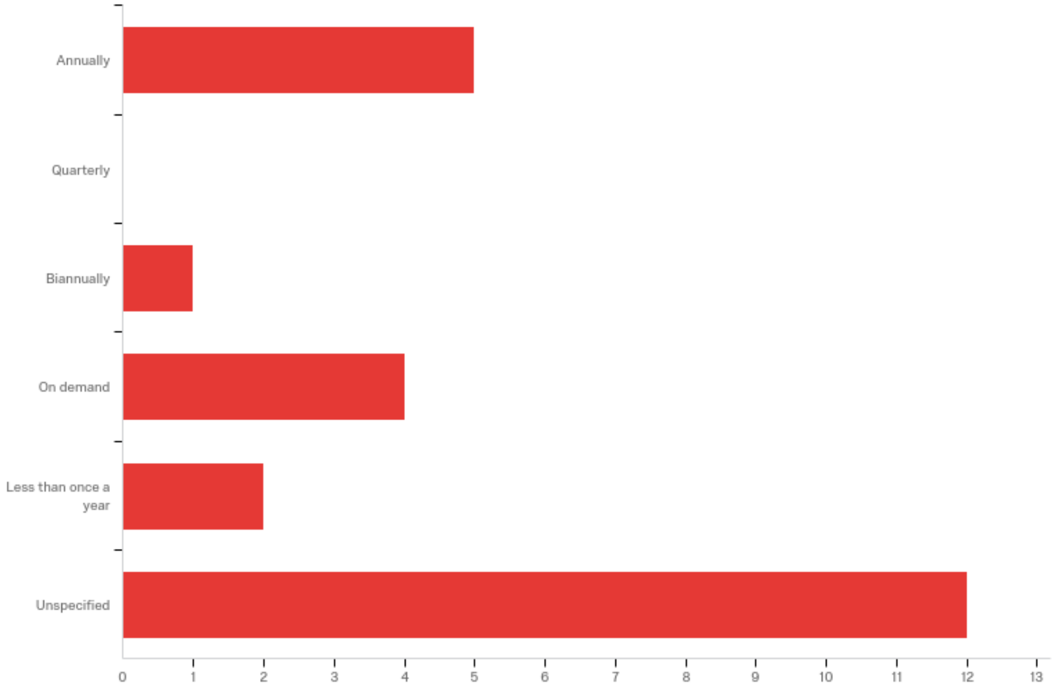


Figure 2.3 Number of respondents showing frequency of risk register update

Program level risk identification and assessment are driven by project development timelines, federal mandates, and revenue and inflation projections (Table 2.2). For project level risks, the factors consistently ranked in the top three were structural condition, life cycle costs, demand/usage, and overall performance (Table 2.3). It is expected that physical condition, demand, and performance will dominate project level risk consideration. The overall performance, on the other hand is a function of condition which is impacted by demand, and how much money is invested. In other words, at the project level, risk assessment is driven by whatever impacts performance. The high ranking of demand/usage in project risk analysis is consistent with its role in project selection decision-making as found in (*8*).

At all three risk levels, funding and policy-related issues stand out. Agencies are always concerned about available funding to maintain performance levels and still be compliant on the federal mandates or state legislations.

Table 2.1 Strategic risk data ranking

| **Data** | **1** | **2** | **3** | **Total*** |
|---|---|---|---|---|
| Funding levels (historic) | 65% | 25% | 10% | 100% |
| Policy changes and political climate | 15% | 15% | 25% | 55% |
| Economy- financial market | 0% | 5% | 40% | 45% |
| Legislative requirements | 0% | 30% | 5% | 35% |
| Personnel changes- upper management | 5% | 15% | 10% | 30% |
| Demand/socioeconomic data | 15% | 5% | 5% | 25% |
| Technology changes/limitations | 0% | 5% | 5% | 10% |
| Outsourcing to consultants/vendors | 0% | 0% | 0% | 0% |

* = 20 agencies responded

### Risk and resiliency considerations

When asked if additional data were considered, 27 percent of responding agencies answered in the affirmative. A list of additional data considered were seismic risk, availability and reliability of performance data, continued use of a systematic assessment approach, and safety data. In addition, two thirds of the agencies considered past risk events and the response in their risk assessment process. Most of these past events were weather-related events. This is evidence that most agencies see value to risk and resiliency considerations in risk management. The combination of risk and resiliency in the risk management process is explored in (*18*, *19*) and is been beneficial to prioritizing mitigation measures for transportation assets.

### Data needs and risk tracking

The majority of agencies, 90 percent, did not identify data needed for the risk identified. In addition, 60 percent of the responding agencies did not specify how frequently to track the identified risks in their risk registers (Figure 2.3), including the 3 agencies that had a data driven approach to tracking risk (Figure 2.4). This can be an indication of a lack of understanding of the benefit of a clear and regular update of the risk assessment process.

Table 2.2  Program risk data ranking

| **Data** | **1** | **2** | **3** | **Total*** |
|---|---|---|---|---|
| Project development timelines | 7% | 27% | 20% | 54% |
| Revenue and inflation projections | 27% | 13% | 7% | 47% |
| Federal mandates and legislative expectations | 7% | 7% | 33% | 47% |
| Historic data | 13% | 0% | 20% | 33% |
| Personnel- expertise and experience | 13% | 13% | 7% | 33% |
| Project delivery schedules | 13% | 7% | 7% | 27% |
| Cost of materials | 7% | 13% | 7% | 27% |
| Program management record | 13% | 13% | 0% | 27% |
| Climate change- flooding, temperature change, etc. | 0% | 7% | 0% | 7% |

* = 15 agencies responded

Table 2.3  Project risk data ranking

| **Data** | **1** | **2** | **3** | **Total*** |
|---|---|---|---|---|
| Structural condition | 27% | 13% | 13% | 53% |
| Life cycle costs | 13% | 7% | 33% | 53% |
| Demand/usage | 0% | 33% | 7% | 40% |
| Overall performance | 27% | 13% | 0% | 40% |
| Funding impacts/tradeoffs | 13% | 7% | 20% | 40% |
| Initial agency costs | 0% | 13% | 20% | 33% |
| Functional condition | 13% | 7% | 0% | 20% |
| Location/Environmental | 0% | 7% | 7% | 13% |
| External risks- litigation | 7% | 0% | 0% | 7% |
| Customer feedback/complaints | 0% | 0% | 0% | 0% |
| Attributes/characteristics | 0% | 0% | 0% | 0% |

* = 15 agencies responded

## Conclusions and Research Needs

The goal of this research was to investigate the state of the practice of how agencies are integrating risk in their TAMP as well as identify research needs to facilitate state DOTs compliance with the MAP-21 and FAST Act. From the state of the practice survey, it is clear that state highway agencies are taking more and more ownership of their TAMP. This is validated in how some agencies are reorganizing their asset management group to include a policy-focused group in charge of development and a technical group in charge of the risk management process and implementation.

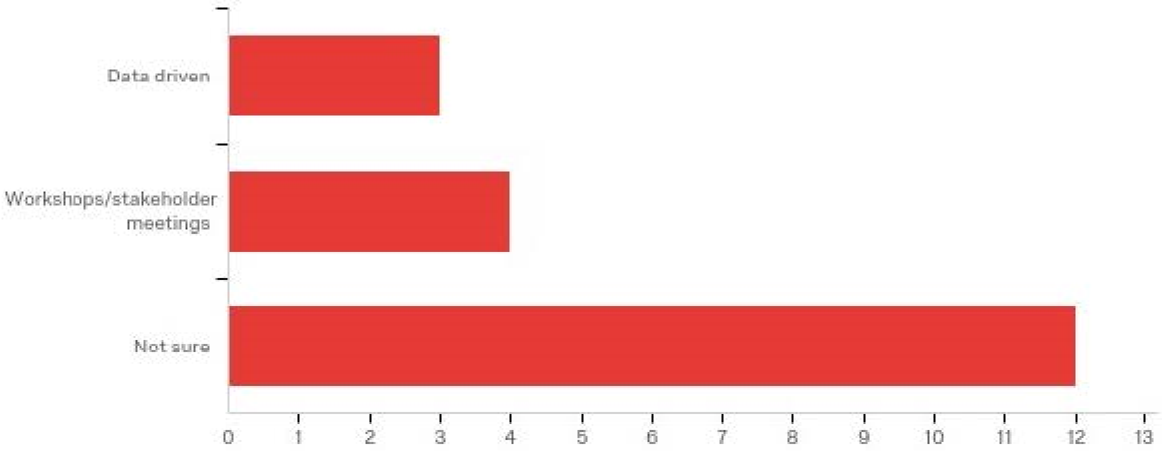


Figure 2.4 Number of respondents on how to track identified risks

Currently, the risk assessment process is driven more by subjective data than by data that is currently tracked. Hence most agencies are unsure on how to track risks. This warrants future research into the synthesis of a composite measure of risk and performance that reflects organizational needs. This composite measure should provide a systematic process for updating the risk assessment process and the risk registers that are generated. It will serve as a basis for comparing alternative improvement strategies (investment and policy approaches) and for tracking results over time.

In addition, there is need to link historic data to risk events to produce a rich database that can allow for predictive and prescriptive modelling. Within the context of risk-based TAMP, leveraging available data and analysis tools helps visualize and articulate, in both qualitative and quantitative terms, how the combination of various risks and strategies would influence performance targets. It paves the way for the consideration of how various risks, such as revenue constraints, policy or upper management personnel changes can impact a state highway agencies' ability to provide services to its stakeholders.

Agencies' reliance on past events prompts the question, what is the overlap between risk management and resiliency planning? Resilience, in this context, is the ability of a system to recover from an unexpected risk event. How does resiliency planning impact risk? Does the two activities augment each other? At which point is that the case and at what threshold is that no longer the case? The preceding questions underscore the need for understanding the relationship between resiliency and risk considerations in effective risk management. There is need for research to document the extent to which implementation of measures across the risk management framework genuinely helps develop the attributes of a resilient transportation infrastructure.

All agencies are using risk registers as their risk management tool of choice. As a result, it is essential to identify how agencies are using or intend to use the risk registers for decision making. In the process, synthesize methodologies for integrating risk registers into the agency's decision-making process. The overall goal of this endeavor is to minimize the duplication of resources for risk management and to foster a sustainable approach to dealing with uncertainties without undermining organizational efficiency.

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# CHAPTER 3. DATABASE DESIGN AND INTEGRATION FRAMEWORK FOR RISK MANAGEMENT FOR STATE HIGHWAY AGENCIES

A paper to be submitted to the Transportation Research Record (TRB).

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## Introduction

Transportation asset management program (TAMP) is defined by United States Code (23 U.S. Code § 101) as "a strategic and systematic process of operating, maintaining, and improving physical assets, with a focus on both engineering and economic analysis based upon quality information, to identify a structured sequence of maintenance, preservation, repair, rehabilitation, and replacement actions that will achieve and sustain a desired state of good repair over the lifecycle of the assets at minimum practicable cost." By this definition, a viable TAMP can only be accomplished if risk considerations are a part of the overall process. Risk management analysis is one of the requirements under MAP-21 and subsequently FAST ACT that elevates TAMP to the same class of management practices expected in the private sector. Risk management has been defined as a process of analytical and management activities that focuses on identifying and responding to the inherent uncertainties of managing a complex organization and managing capital facilities (1). According to the International Organization for Standardization (ISO), risk management is the effect of uncertainty on objectives (2). Hence, a risk-based asset management approach is tasked with the documentation of risks that affect the department of transportation's (DOT) ability to meet its objectives, assessment of the impacts of the risks as well as proffering mitigation (3). At the core of this, is the ability of transportation agencies to have a mechanism for measuring the identified risks, as this will help drive the potential mitigation activities. The monitoring and updating of the risk management process is essential to TAMP as it will ensure that new risks are identified and that existing risks are tracked and updated (1). In addition, this would enable the agency to quantify the likelihoods of these risks. This ability to track and quantify risk would benefit the risk classification process (4) and its integration into an asset management plan. Furthermore, it will help ensure that the financial plan and investment strategy components of the TAMP are suitable to ensure that the agency continue to fulfil its primary responsibilities.

A 2011 national scan of how state DOT agencies are using risk management revealed that less than 13 agencies had a comprehensive risk management framework at the enterprise, program and project levels (1). The enterprise level risks affect mission, vision, and overall results of the asset management program. The program (business line) risks affects DOTs ability to deliver projects and meet targets within a program. These may include organizational and systemic issues as well as revenue and economic uncertainties that in general cause project delays. These issues can be multivariate. Examples include project delivery risks, revenue uncertainties, cost-estimating processes, revenue and inflation projection inaccuracies, construction cost variations, materials price volatility, data quality, personnel, etc. Project/asset level risks affects scope, cost, schedule, and quality of projects. In contrast to programmatic risks, project risks are related to specific projects. In other words, there are inherent issues in a given project that may result in a project delay. Examples include hazardous materials, geology, environmental issues, right-of-way issues, utilities, project development timeline/delays, scope growth, cost overruns, project delays, etc.

In 2017, a national scan was undertaken on the state of the practice of risk management implementation among State Highway Agencies (SHA)(described in Chapter 2), and the number of agencies that have risk registers at the enterprise, program and project levels has almost doubled (5). A review of the TAMP documents that have been uploaded to the AASHTO TAM portal by various state DOTs show that most agencies have similar methodologies for risk management. It involved setting up a risk task force that typically will consist of data owners, data managers, program managers (bridge, pavement, safety, etc.), and an asset management committee tasked with developing and implementing the department's TAMP to ensure it satisfies Federal requirements, coordinating asset management activities across all department bureaus and divisions, and facilitating progress towards improving asset conditions, inventories and data sharing capabilities (5, 6). Hence, the task force represents all the relevant stakeholders involved in risk management decision making. The task force will then convene a risk workshop. From this risk workshop, risk registers were compiled to represent all the risk events that the agency considered important along with mitigation plans. This consultative process did not allude to any development of datasets on various risk events, processes, and measures to be able to quantify or track risk. In addition, the 2017 study on the state of the practice for integrating risk management in US highway agencies found out that majority of agencies did not identify data needs along with the risk identification process and as a result were unable to agree on frequency and process for tracking identified risks (5).

Effective TAMP practices involve data-driven decision making leading to timely application of the right treatment. TAM relies on combining information from multiple sources: road network and inventory, bridge and ancillary assets inventories (which are often maintained separately for different assets), inspections, capital projects—historical and planned, maintenance activities, work requests, traffic, freight movements, vehicle crashes, soil characteristics, weather, and other land and environmental data sets. Many agencies achieve this data integration through on-demand, time-consuming efforts that require specialized expertise (7). As a result, these efforts are ad-hoc making it untenable for a risk management workshop to generate or update risk registers. This explains why although risk management integration is still emergent among SHA, a lot has been said about the concept of risk management but not much about its implementation. This is contingent on the fact that there is no integrated database of all the SHA divisions' data that can be used for risk management. To mitigate this, a comprehensive cross-asset database of all the important data items that agencies need to successfully execute their risk-based asset management plan need to be developed. This will form the basis for tracking and updating risk registers, quantifying the relationship between risk and consequences, and integrating the results in a geographic information system (GIS)-enabled dashboard application for visualization and decision support.

Hence, the objective of this study is to propose a framework for developing a cross-asset comprehensive database for risk management that integrates all the risks that an agency has identified through its risk identification process. The database will facilitate data-driven risk identification as well as a data-driven approach to update and track risk registers. In addition, with a comprehensive database, it becomes feasible to synthesize a composite measure of performance that encompasses various DOT departments and assets.

## Background

Risk management is not a new concept, but among SHA, it is still emergent in implementation as well as practice. The process of risk management can be generally divided into three phases: identification, analysis and response (8). It will not be farfetched to posit that an effective response to risk can only be accomplished if the process and data used to estimate the response is contextually accurate (9). The availability of accurate data is vital for any risk-based asset management program. Data are needed for defining agency objectives, risk identification and measurement, supporting the decision-making process, and monitoring progress toward objectives (10). Furthermore, asset level data such as—age, condition, failure rates, and maintenance activities as well as consequences of failure to the user (user cost), the agency (agency cost), and the environment (external cost) —are very critical to risk-based decision-making framework (10). However, these data are not always collected together nor managed in one database or by one department. As a result, the data are not always in a usable format nor exist under various asset management systems requiring integration. It is very important for TAM processes to see the assortment of datasets as a whole and not just as a sum of the parts since the most accurate picture is one that takes from all sources and produces an output that is unique to all its sources. This is very significant because the overall objective is to synthesize useful trends and patterns that can be used for decision making (11).

Data integration is defined as the process of combining data residing at different sources or in different formats and providing the user with a unified view of these data (12). For the benefit of TAMP, the Federal Highway Administration (FHWA) defines data integration as “the method by which multiple data sets from a variety of sources can be combined or linked to provide a more unified picture of what the data mean and how they can be applied to solve problems and make informed decisions that relate to the stewardship of transportation infrastructure assets” (13). Hence, data integration is essential to transform data into useful information that can support the different organizational levels of decision-making. The challenges facing a successful data integration implementation has been highlighted as the biggest obstacle to risk-based asset management practice (14, 15). This is a fundamental requirement for effective TAM (13).

In industries such as banking and finance, insurance, and nuclear power sector, there is usually a clearly defined database that feeds risk management (9, 16). However, among SHA, managing an assortment of assets with varying degree of granularity across multiple divisions answering to the same central office with an overall goal and objectives, can create a nightmare for a database integration effort that is appropriate for risk management. The basis of this study aims to provide a solution to this nightmare by developing a comprehensive database needed for integrated risk management. Specifically, it proposes a framework that simplifies the integration of existing databases and infrastructure management systems, as well as identifies additional data items that need to be collected or better integrated for successful risk management.

## Data Integration Challenges

Effective risk analysis relies heavily on objective and quantifiable data. The data required to run complex risk analysis resides in multiple systems across the SHA and in different schemas. The difficulty associated with organization and normalization often presents the biggest challenge in receiving relevant and timely risk information. Tactical database and spreadsheet tools are inflexible, difficult to maintain and generally unreliable. The lack of integration between systems poses big challenges to transportation agencies' efforts to integrate risk management in their TAM. These challenges can be grouped into the three different classes: systems, logical, and social and administrative challenges (17). In the following sub-sections, each one is discussed separately.

### Systems Challenges

The systems challenges that impact data integration are the most observable. Transportation agencies, by their nature, require large quantities of data to support repetitive operations as well as to respond to planning, design, construction, and other programmatic needs

(13). These needs warrant the different divisions within a transportation agency to individually collect the necessary data needed which then ends up on different systems in each division. Essentially, the challenge is to allow these dissimilar systems to talk seamlessly to one another. In addition, executing queries over multiple systems efficiently is especially difficult (17).

### Logical Challenges

The second set of challenges result from the way data are logically arranged in the data sources. Most transportation agencies that maintain databases of roads break them into logical segments to create unique transportation features according to some business rules, such as pavement type, traffic volume, jurisdiction, or at intersections (18, 19). These differences in the original need for transportation databases create a difficult arena for data integrators as they result in data being organized into different schemas depending upon which segmentation or agency unit is driving the collection. In these data models, the schema is identified by tags, classes, and properties (18). Hence, when data come from multiple sources, they usually are disparate creating a logical challenge for data integration.

### Social and Administrative Challenges

The benefits of data integration when fully implemented are well known (17). However, there are institutional barriers, not technical, that are more commonly responsible for a data integration falling short of full implementation (18). The first challenge may be to find a particular set of data in the first place. For example, in situations where DOT performs in-house maintenance activities which are not properly recorded electronically in terms of their location and extent (19), a special effort is required to locate and scan them all. Even when the data exists, sometimes owners of the data may not be allowed to cooperate with an integration effort.

For instance, traffic safety data involving medical records or law enforcement may have legitimate legal reasons for not sharing that data.

### Synthesis of the Data Integration Framework

This section strives to layout a conceptual framework for data integration for risk management while providing recommendations for tackling the data integration challenges. As already established, the goal of data integration is to combine data in various formats and from various sources to provide the user with a unified view of the data. To this end, a data integration system should comprise a global schema, data sources, and the set of rules relating the global schema to the sources. In short form, a data integration system I = fŋ(G,S,M) where G is the global schema, which represents all the important variables for risk management in this study; S is the source schemas, which contain information about the variables in G; and M is the mapping functions or transforms that relates G to S (12). This can be represented graphically as shown in Figure 3.1 (17). Data sources can be relational, flat files, XML or any other format that contains structured data. In a SHA, the data sources can be the various management systems, such as pavement and bridge management information systems. The mapping functions request and transforms data from the sources providing a data dictionary service that shows how data from one information system maps to data from another information system. The mapping function provides a way for the data sources to be independently managed by the various divisions of the DOT. The global schema or central data warehouse abstracts all source data. Between the sources and the global schema, a set of transformations are used to convert the data from the source schemas into the global schema (17). This set of transformations act like an application programming interface (API), which is a set of tightly-controlled rules or subroutine definitions and communication protocols between two programs (20). In this case, the API provides a method of communication that the global warehouse and data sources can handle. Collectively, changes could be made to both the warehouse and data sources, presuming they are reflected in the API, and there will be no break in the exchange of information.

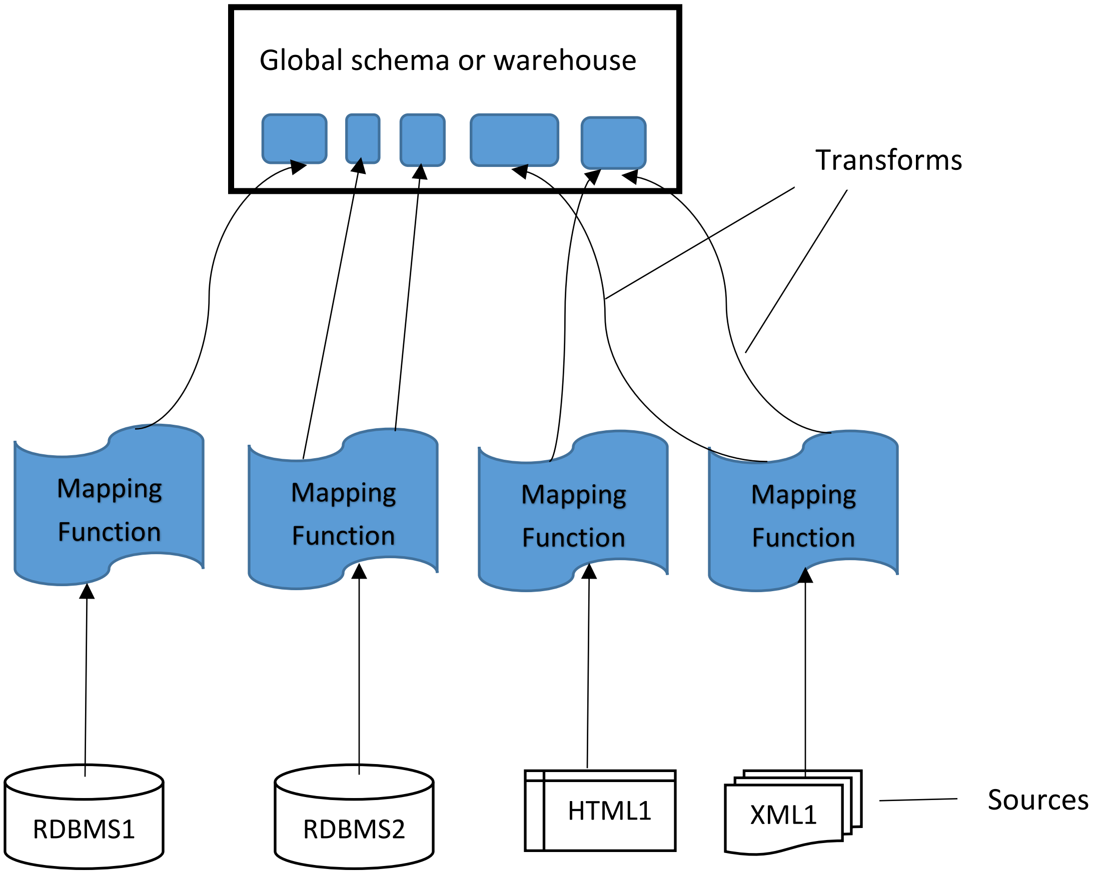


Figure 3.1  The basic architecture of a data integration system (17)

The implication of having the API for the SHA is that each division can continue to manage its database per usual. The API will be designed such that it is able to extract the required information from the various databases and transform it into what is needed to populate the risk management database.

## Data Integration Framework

Based on the challenges to data integration, recommended mitigation options, and layout of the basic data integration architecture presented earlier, Figure 3.2 proposes a framework for developing a risk management database. It utilizes a step-up process that provides a way to transform agencies' raw data into the metrics and dimensions needed to create easy-to-understand reports and dashboards for decision making. This process begins as a qualitative process and transforms into a quantitative process for visualization and modelling. This chapter focuses on data elicitation and data aggregation. Risk calculation and decision making will be covered in Chapter 4. This chapter only addresses the processes leading up to the creation of the risk management database that will be used for risk calculation and decision making.

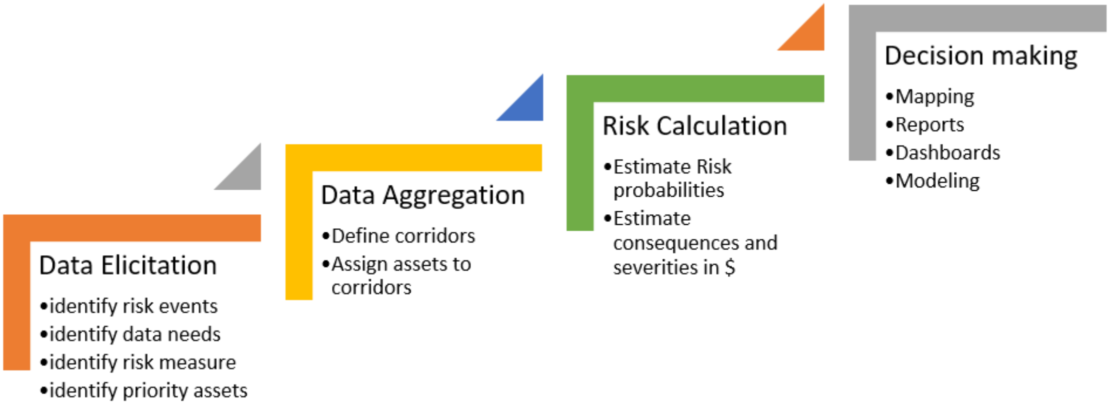


Figure 3.2 The data integration process

## Data Elicitation

Fields such as business intelligence and decision support systems have made great strides with advancement in technology. The emergence of big data has propelled these fields into the next frontier for innovation (21) and at the fore front of the data science study in both academic and business communities in the last two decades (22). State highway agencies have embarked on a data collection spree since the passage of the MAP- 21 legislation. The sheer magnitude of this data collection endeavor can be accurately classified as big data.

Big data, by its nature, do not have form nor structure prompting the rise of business intelligence and analytics. Hence, data elicitation is the process of trying to structure these data to make it accessible and usable (23, 24). In other words, data elicitation is the process of identifying the data elements that are relevant to the task at hand and how to synthesize that data to produce the required information or business intelligence.

The purpose of this section is to discuss various ways of identifying the required data elements that could be accessible and useful for a risk management database. Understandably, this process will drive the success of the data aggregation, risk calculation and decision-making processes.

### Risk register as a tool for data and risk event elicitation

Risk register is the most popular, if not the only, risk identification tool used by SHA (5, 25). A risk register is a simple spreadsheet or matrix that summarizes an agency's risks, how they are analyzed, and records how they will be managed and by whom (26). Risk registers can be customized for any agency. The 2017 survey of how SHA are integrating risk in their TAMP (5), as well as a review of the 26 SHA TAMP documents, as of August 2018, uploaded to the AASHTO TAM portal, show that most agencies synthesized their risk register during a risk management workshop. The workshop is usually attended by the relevant stakeholders in a SHA from the various divisions, units, or departments as well as a liaison from each of the assets. This workshop provides a framework for SHAs to do cross-asset risk identification. This multi-level and multi-disciplinary approach ensure that risks are linked to strategic goals and facilitates risk mitigation at its highest level (5). The risk events identified from these workshops represent a synthesis of network level, program level, as well as project level risks. In short, this workshop identifies all the risk events relevant to the agency and can be a useful tool for data elicitation for risk management.

While identifying risk events is an important outcome of the workshop, it fails to address the identification of data associated with these events. Addressing data identification provides opportunity for SHAs to evaluate their data collection and integration methodologies in a way that addresses data limitations to properly track and update risk registers. In addition, the risk workshop can go a long way to addressing the system challenges of data integration discussed in the preceding section. Having all division heads and asset liaisons in the same room provides a great opportunity to define or refine data collection rules that ensure various divisions manage their data in systems that can communicate seamlessly with each other. It provides a solution to mitigating the social and administrative challenges facing data integration as it allows all the data owners to be on the same page. This qualitative process can be very useful for identifying relevant datasets to integrate as well as missing data to collect.

Risk registers from twenty six TAMP documents on the AASHTO TAM portal were reviewed to gauge common risks that agencies have identified. Risks were generally organized by levels – agency, program and project, or by categories – as defined in NCHRP Project 08-93 report, Managing Risk across the Enterprise: A Guidebook for State Departments of Transportation (27). There were still some agencies, such as Iowa DOT, that did not employ any template in summarizing their risk registers. Common risk events were categorized in one of the following:

1. Finances- risks related to the long-term stability of asset management programs such as:
    a. Unmet needs in long term budgets
    b. Funding stability
    c. Exposure to financial losses

2. Information and Decision- risks related to the implementation of asset management program such as:
    1. Lack of critical asset information
    2. Quality of data, modeling or forecasting tools for decision making
3. External Risks- these are risks involving both human-induced and naturally occurring threats such as:
    1. Climatic or seismic events - extreme weather, flooding, earthquakes, slope failures, rock falls, lightning strikes
    2. Winter weather operations
    3. Climate change
    4. Terrorism or accidents
    5. Paradigm shifting technologies (e.g. automated vehicles)
4. Asset Condition - risks associated with asset failure such as:
    1. Structural
    2. Capacity or utilization
    3. Reliability of performance
    4. Aging
    5. Soil and subsurface utilities
    6. Maintenance or operation

These common risk events can provide a way for the SHA to organize their overall data collection and management process to support risk management. The focus is not on identifying new data to collect but to identify existing data that quantifies risk events. This ensures data is managed in a way that can support the risk management process, especially as it feeds the decision-support framework. Table 3.1 summarizes risk events mentioned in the registers and their frequency.

Table 3.1 Summary of risk events identified

| **Risk Events** | **Agency Count** |
|---|---:|
| Financial risks | 21 |
| Business operations risks (personnel changes and knowledge gap) | 21 |
| Information and decision risks | 18 |
| Bridge failure – structural (excluding vehicle impacts) or scour related, resulting in loss of service | 13 |
| Condition related risks/Performance related risks | 13 |
| Extreme weather event | 12 |
| Assets are damaged or destroyed due to flooding | 11 |
| Heavy truck volume growth/legal weight increase | 9 |
| Bridges are damaged or destroyed due to scour | 7 |
| Climate change/Increased ongoing, seasonal weather events/freeze/thaw cycles | 7 |
| ITS or traffic control failure – resulting in safety impact | 6 |
| Scope growth/growth in size of network relative to funding | 6 |
| Rock fall incident with loss of function/mobility (several days) or fatality | 6 |
| Landslide – loss of road and mobility | 6 |
| Culverts and other drainage facilities fail (blockages or overtopping) unexpectedly. | 6 |
| Capacity improvements projects are delayed/deferred maintenance | 5 |
| Retaining walls (requiring maintenance but no mobility impacts)/slope failure | 4 |
| Assets are damaged or destroyed due to earthquakes | 4 |
| Assets are damaged or destroyed due to wildfires. | 4 |
| Assets are damaged or destroyed due to vehicle impacts and/or hazardous materials spill. | 4 |
| Bubble in asset replacement needs due to uneven asset age distribution | 4 |
| Negative Public opinion/public involvement delay killing projects | 4 |

Table 3.1 continued

| **Risk Events** | **Agency Count** |
|---|---|
| Assets are damaged or destroyed due to hurricanes. | 3 |
| Assets are damaged or destroyed due to retaining wall failure | 3 |
| Sinkholes emerge under or near roadway sections compromising foundation. | 3 |
| Winter weather treatments and impacts on pavement deterioration | 3 |
| Socioeconomic risks- population growth/ shift to urban areas/land use | 3 |
| Avalanche requiring maintenance but no/minimal delay | 2 |
| Assets are damaged or destroyed due to tornadoes. | 2 |
| Travel mode changes | 2 |
| Highway safety | 2 |
| Tunnel collapse/closure due to safety incident | 1 |
| Subsurface utilities impact by others in ROW (and below roadways) | 1 |
| Make projects more complex | 1 |

### Risk register as a framework for identifying assets for inclusion into TAMP

Most asset management programs focus on pavements and bridges. However, there are other ancillary assets that are needed to ensure safe and efficient operation of a transportation network. Including these in a risk management program should be logical however, there is need for a business case to make about the relative benefits of adding these ancillary assets. Limited resources and budget constraints often force agencies to make difficult decisions regarding resource allocations. Therefore, agencies looking to expand their asset management programs to include ancillary assets need a means of determining the benefits and costs associated with system development, data collection, and data management. Some studies have looked at the criticality of assets for inclusion in TAMP (28, 29, 30). This consideration is important in designing the framework of a database needed for risk management. A database must account for all critical assets, as long as there is data to justify their inclusion and impact to the overall agency goals and objectives.

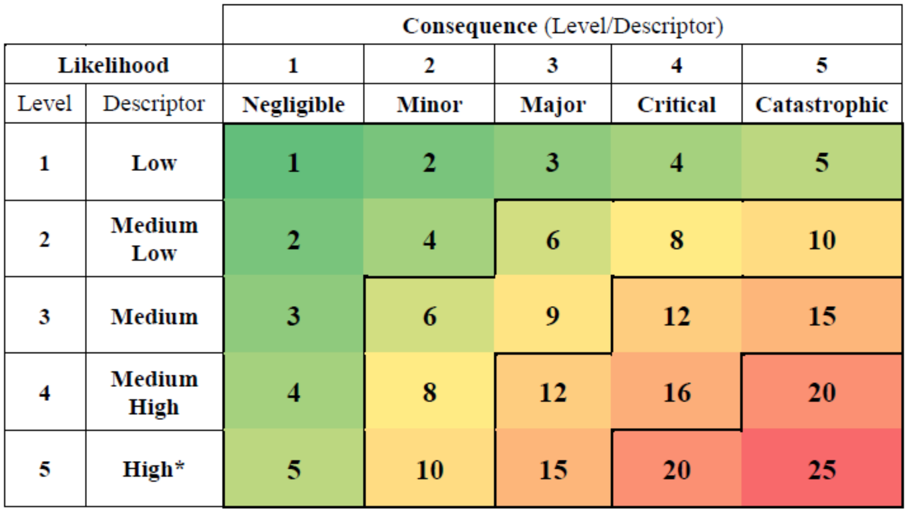
Risk registers are designed to capture risks agencies consider important in fulfilling their strategic objectives and goals. Hence, the risk identification process is a good way to understand what assets agencies deem important for inclusion into their formal risk management. Based on the risk registers reviewed in the previous section and summarized in Table 1, agencies explicitly identified assets that they considered important in their risk management efforts. The other assets identified, besides pavements and bridges, were Intelligent Transportation Systems (ITS) devices and elements, culverts and other subsurface drainage facilities.

The purpose of this study is to propose a framework for designing a database for risk management process. It does not define what assets are important, instead it is designed with the view that agencies could prioritize assets according to individual agency needs as they deem fit.

### Risk register as a framework for identifying risk measures

In agencies' risk registers, risk was evaluated in terms of likelihood of service interruption and the impact based on a low to high severity scale (5). The scale in Figure 3.3 shows the risks identified by the task force along with their determination of the likelihood of the event occurring, and then assessed in terms of its consequence, from catastrophic to negligible. For example, if the risk category is information and decision-related, the agency will rate the likelihood of the event happening to be 4, and the consequences to be 3, the potential impact will then be that investment decisions will not be reliable.  The same approach can be applied to assessing opportunities.

However, this qualitative process does not provide context for the agencies to visualize how the combination of various risk events and strategies would impact strategic goals and



| | | **Consequence** (Level/Descriptor) | | | | |
|---|---|---|---|---|---|---|
| **Likelihood** | | **1** | **2** | **3** | **4** | **5** |
| Level | Descriptor | **Negligible** | **Minor** | **Major** | **Critical** | **Catastrophic** |
| **1** | **Low** | **1** | **2** | **3** | **4** | **5** |
| **2** | **Medium Low** | **2** | **4** | **6** | **8** | **10** |
| **3** | **Medium** | **3** | **6** | **9** | **12** | **15** |
| **4** | **Medium High** | **4** | **8** | **12** | **16** | **20** |
| **5** | **High*** | **5** | **10** | **15** | **20** | **25** |

Figure 3.3  Risk Matrix (2)

performance targets.  It also does not address how the agencies will use the risk registers for decision making. Having all stakeholders in attendance for the risk workshop allows them to understand context and other items the qualitative process does not provide. It provides a platform for synthesizing risk measures from available data or expert elicitation.

Historical data can be an effective tool to understand system performance. This data can be very important for analyzing the causes of asset failures, including spatial and temporal dynamics, to prioritize identified risks and develop a quantitative risk metric. These metrics help to answer pertinent questions such as: what was the impact of the risk event on the infrastructure? Was that impact expected? If the impact varied from expected, why? These questions will require developing datasets on various risk events, processes, and measures to be able to generalize across risk events as well as agencies. Even though risk measurement is not the same as risk management (31, 32), the process of risk measurement can provide insights into how organizations could manage similar events. This is very important since the intent of risk management is not only to contain current risk but to mitigate future risk in order to deliver on its strategic goals.

It is difficult to understand what cannot be measured. Hence, the risk mitigation can be impacted by lack of a well-defined risk measure. For example, if there were two possible mitigation for a risk occurrence, the lack of a risk measure makes it difficult to employ an optimization process to make the best decision between understanding the calculated risks and the cost of mitigation (33).

### Proposed risk workshop outline

It has been established that the risk workshop is the risk management tool of choice by SHA. The overall goal of the risk workshop is to generate risk registers that will drive the risk management process, informing decision making as well as providing guarantee that threats to agency goals have been identified and adequate mitigation protocols put in place to ensure seamless operations.

A successful risk workshop should have the right composition of internal and external stakeholders. The external stakeholders can be from other SHA, academia, and if possible from the private sector so that SHA can have a balanced approach to risk identification that not only documents existing threats but pre-empt future threats. In addition, the risk workshop should be highly participatory ensuring extensive interactions across the agency’s asset managers, departmental heads, and senior executives, as well as those in specialist disciplines such as governance, compliance, risk management and audit. The end goal is the formulation of effective risk registers. The following is an outline of the workshop:

- An opening session on the function and goals of risk management referencing the agency existing policies
- A review of the basic risk management process encompassing
    - Risk event identification

  - Priority assets
  - Data needs
  - Evaluation of risks/risk measures identification
  - Application of risk tolerance
  - Mitigation strategies
  - Tracking effectiveness of mitigation strategies
  - How to track new risks/revise existing risk events
- Breakout session by asset types
  - Introduction of a generic risk register containing the key fields to be completed
  - Risk event identification by asset type
  - Data needs and risk measures identification for each risk event identified
  - Risk mitigation strategies and monitoring of effectiveness
- Full session
  - Harmonize risk event identification, resolving overlaps and duplicates
  - Describe risks in clear and plain manner
  - Identify most appropriate risk owners
  - Identify relevant existing data and data needs for evaluating risks in terms of probability and impact in monetary terms
  - Identify risk mitigation strategies
  - Identify relevant risk metrics for tracking and measuring risk events and mitigation, residual risks and additional mitigation approach
  - Identify risk levels and triggers and clear line of sight between risk management and day-to-day management

  - Identification of level of aggregation- highway (linear) corridors or regional (area) corridors
- Closing session for compilation of risk registers, data needs, priority assets, risk measures and identifying cross-asset collaborations to enrich the risk management process

## Data Aggregation

Data aggregation is where data is pulled from all the identified sources of data for risk management.

### Logical Segmentation for Risk Management

Transportation agencies' operations will always require data collection and management specific to individual assets. For example, the pavement management system will aggregate data at the project level where each project was constructed at the same time, maintained at the same interval, with the same pavement type and travel experience. On the other hand, the pavement marking management system might be maintained and collected by the milepost. To mitigate the logical challenges of data integration and preserve the flexibility for risk mitigation at the level of its biggest impact on overall agencies' goals, this study is adopting a corridor approach to risk management data integration and management. GIS becomes the tool for integration since most DOT data are spatially-enabled.

Corridor segmentation allows the SHA to prioritize their networks that best reflects their funding decisions, political realities, as well as usage of their network. In addition, it provides a common logical segmentation for data integration that drives decision making. Corridor segmentation allows for the integration of asset and risk event data at a granular level that makes the most sense from an investment and programming perspective. For example, if a storm were to take out a bridge, the impact of that risk event is not just at the bridge, but all the assets connected to that bridge. Decision making based solely on the bridge will only capture the replacement cost of the bridge and will miss out on the full cost of the risk event. To simplify the process, each agency can use its already existing corridor segmentation that fulfills its investment decision making and programming analysis.

### Corridor segmentation

The corridor segmentation can be defined by a point, linear or area extents based on what the agency determines to be the common denominator for tracking costs of the risk event. For instance, risk assessment that is focused solely on road users can be sufficiently defined by linear extents such as highway corridor. On the other hand, risk assessments based on land use, watersheds, and population will benefit from an area or regional corridor such as counties, districts, or urban areas. In any case, the framework is designed to work regardless of the level of segmentation as long as there is a process to integrate the input to the corridor.

## Geographic Information System (GIS) as a Data Aggregation Tool

Transportation systems in general are made up of a network of spatially-distributed system of physical assets such as bridges, pavements, and other assets in the right of way (7). GIS uses a geospatial system for capturing, storing, analyzing, and displaying data related to positions on the Earth’s surface. As a result, it becomes a natural choice for data management, risk analysis, and visualization especially for data with spatial properties. GIS is able to process geographic data from a variety of sources and integrate into a single database as shown in Figure 3.4 (34). Through data overlays and integration of various risk events and corridor characteristics, spatial analysis can yield useful results for event impact prediction, corridor analysis, as well as potential for developing robust risk models.

## Database Contents

The intent of database integration framework is to produce a dynamic risk management database that will take the place of the static risk registers document. This database becomes a dynamic repository of knowledge and business intelligence by providing a platform for risk analysis, tracking, and updates. Patterson and Neailey (35) carried out an extensive literature review of what information should be contained in a risk register. Based on that review and the uploaded TAMP documents on the AASHTO TAM portal, it was proposed that the risk management database at a minimum contain the following information for each corridor and risk event:

- Risk Identification Number that ties all corridors with the same risk as well as track risk dependencies
- Brief explanation of the risk
- Asset inventory- number and type of assets on the corridor
- Condition of assets based on agreed upon performance measures
- Environmental level data- physical attributes, proximity to watershed, geographic properties, soil type, etc…
- Socio-economic indicators- population, land use, traffic volume
- Probability value- probability or likelihood of the risk occurring, estimated during the risk calculation stage of the data integration framework
- Risk measures- based on the elicitation stage and determined during the risk calculation stage
- Impact measure- impact of the risk in monetary terms value determined during the risk calculation stage

- Area of impact- estimated as a function of the geographic area as well as the socio-economic markers near the corridor

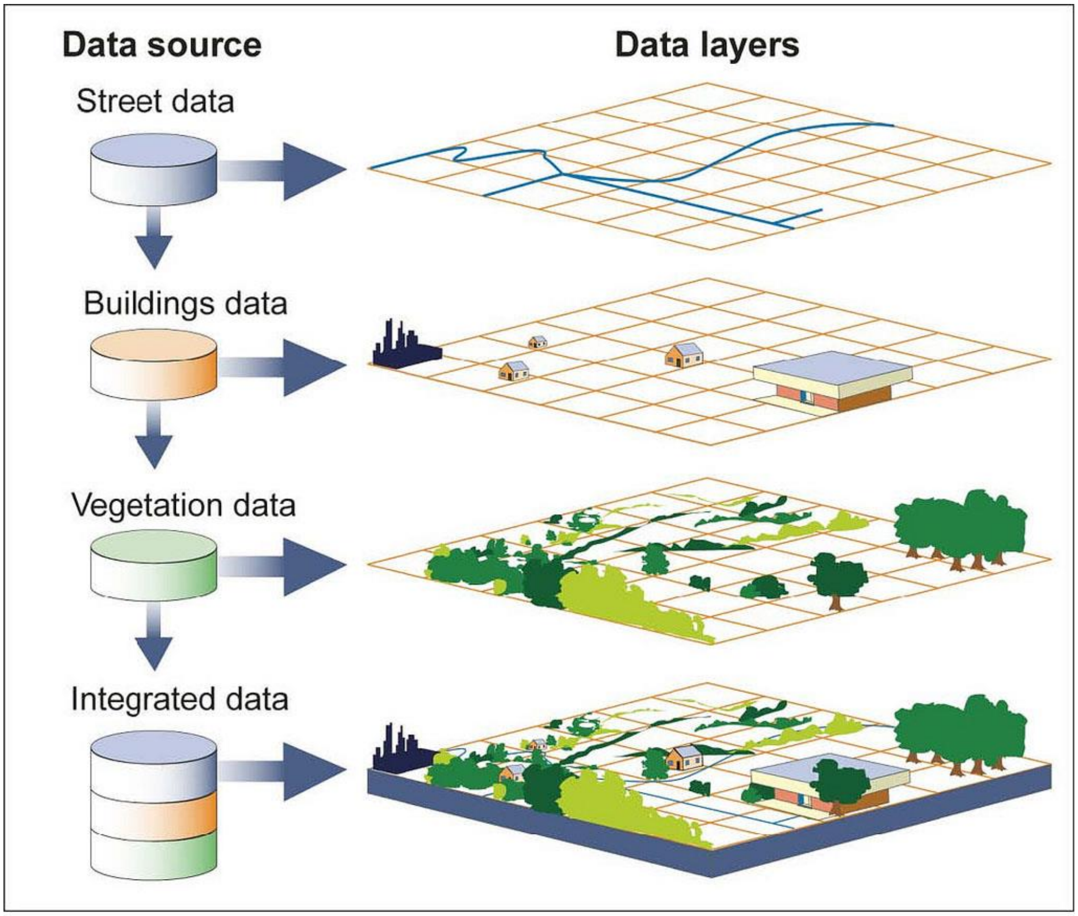


Figure 3.4 GIS overlay capability (34)

- Severity of the risk event- function of the area of impact
- Ranking of each individual risk within the corridor. Ranked risks are those with a high severity and high consequence within the corridor
- Total risk on the corridor- weighted sum of all the risks in the corridor
- Risk monitor- indicates if the risk has increased, remained the same or decreased in severity since last available data collection
- Risk owner- which agency is responsible for the risk

- Risk mitigation plans- based on risk management and data elicitation workshop
- Risk status- indicates whether the risk is active or whether it has been mitigated
- Risk potential- indicates whether the risk can lead to other risk and the potential for a cascade effect

This information is designed to create a framework for the risk management database to be able to carry out the risk identification as well as provide insight into how the risk can be quantified based on available data.

### Closing the Loop (How it all fits together)

There is no doubt that risk management requirements of MAP-21 and FAST Act legislation are a game changer for many SHAs. One of the biggest implications of this is the need to radically improve the SHA’s data capabilities and architecture associated with risk management, thus enabling all stakeholders to get a clear and comprehensive view of the agency’s risk exposure. These requirements are not only a new set of obligations for the SHA but are also a tremendous opportunity to strengthen existing initiatives to address data shortcomings associated with risk management. These implementations may differ from one agency to another, but the goal should be the same: establishing a single source of data for risk management that can be accessible and useable for driving investment and programming decisions.

Figure 3.5 Database integration framework

The framework proposed in this chapter and detailed in Figure 3.5 does not require a complete overhaul of the agency’s data management process but instead streamlines the process to enable the data to be relevant across divisions and minimizes costs due to duplication of efforts. It also provides a way for the agency to quickly identify what missing data is needed to

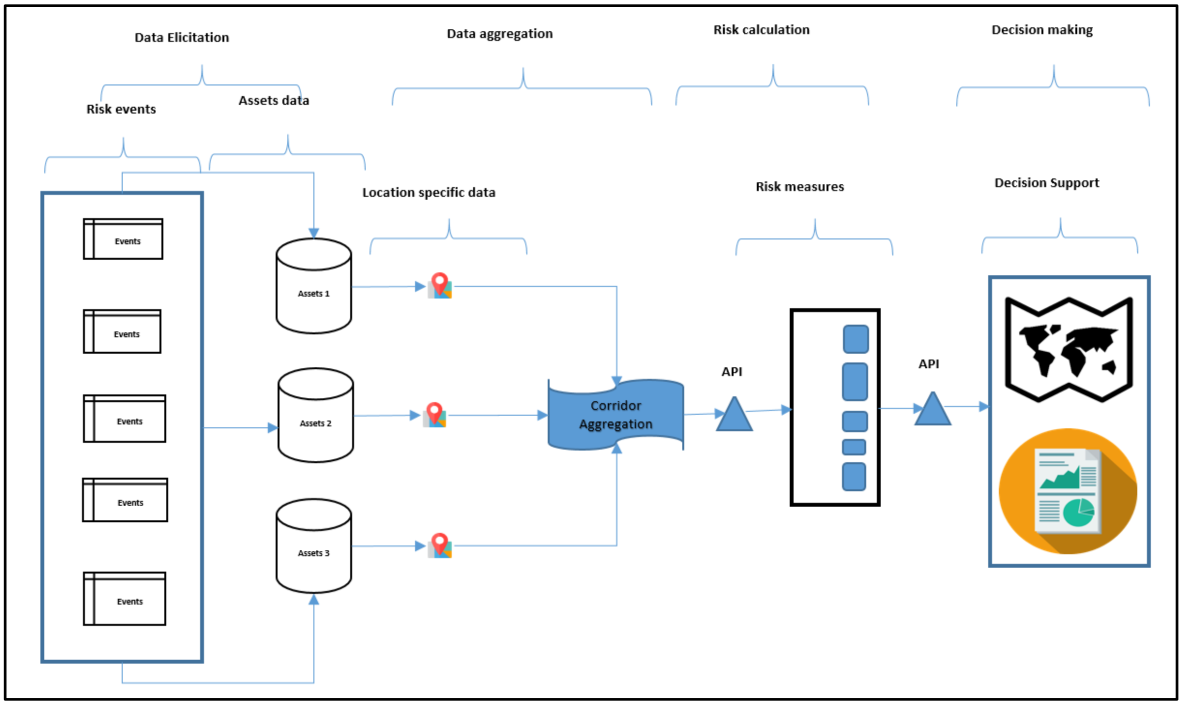


Figure 3.5  Database integration framework

complete their risk management process as well as improve quality assurance of their current data collection process.

Based on the risk and data elicitation process, the available data is then integrated with risk event information and aggregated to the corridor segmentation using an API that will transform all the data into a risk measurement database. In cases where the risks cannot be quantified, expert knowledge estimation will suffice. As new data is imported, APIs will aggregate it with existing data and update the database providing a means of tracking performance of the mitigation plans (36).

The contributions of this study include a database integration framework, design of APIs for extracting data for risk calculations, and APIs to display a suite of dashboard applications for visualization, data mining to support funding, investment strategies as well as operational decision-making.

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# CHAPTER 4. DATABASE IMPLEMENTATION

A paper to be submitted to the Journal of Transportation Engineering, Part B: Pavements

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## Background

Transportation is the mainstay of economic activity, connecting producers with supply chains, customers with products and tourism, and people with their workplaces, homes, and communities across both urban and rural lands. In 2017, the transportation sector added over $400 billion to the U.S. gross domestic product (1) while moving more 19 trillion dollars of shipments value, about 60% of which were moved on road. The demands on the transportation system lead to ongoing deterioration of roadways and bridges that must be repaired, rehabilitated or replaced to preserve the integrity and reliability of the transportation system. Transportation managers must continually evaluate system safety, performance, condition, and vulnerabilities in the context of available funding to make good transportation investment decisions. The ongoing costs associated with preserving the condition and performance of existing transportation assets are significant. Billions of dollars are spent each year by state and local government agencies to hold deterioration at bay, so the transportation system can continue to support user reliability and safety with minimal disruption. The need to efficiently manage transportation system investments has led to a recognition of the benefits of managing assets using a data-driven systematic approach generally referred to as Transportation Asset Management (TAM). AASHTO defines TAM as an intentional and systematic process of operating, maintaining, upgrading, and expanding the capacity of physical assets throughout its lifecycle (2). TAM forces state transportation agencies which are public institutions to adopt the same business practices that the private sector is defined by in its stewardship of public funds. According to the International Standards Organization documents in ISO 55000 and ISO 31000 (3, 4), risk management is the core principle of asset management. Hence, TAM cannot be effectively done without quantifying and qualifying risk, and how it will be managed to accommodate community values related to accepting and managing risks. To that end, on July 6, 2012, the Moving Ahead for Progress in the 21st Century Act (MAP-21) was signed into law by President Obama. MAP-21 requires states to develop a risk-based asset management plan for the National Highway System (NHS) to improve or preserve the condition of the assets and the performance of the system. MAP-21 sparked a paradigm shift from traditional formula-based emphasis to a performance-based approach for TAM (5). Hence, the business of all state departments of transportation (DOTs) is to identify, manage and communicate acceptable risk, risks strategies, and what can and cannot be accomplished given the available resources. This process of risk management by nature is very data intensive since you cannot manage what you cannot measure (6, 7).

As a result, state DOTs and other transportation agencies collect, exchange, manage, and use substantial quantities of data and information for project development and subsequent management of the physical assets for which they are responsible. These agencies devote considerable resources to data collection and storage and often face challenges such as duplicating effort or gaps in data collected by various organizational units; ensuring that data sources are well documented and data is current; and providing the various units responsible for planning, design, construction, and operations and maintenance of system assets with access to reliable and current information for decision making.

Persistent evolution of data and information technologies present challenges as agencies seek to ensure that the transportation system delivers high performance and the agency performs its functions effectively and efficiently. Remote sensing, Lidar, GIS, 3-D graphic displays, and virtual reality (to name a few of the newer developments) are supplementing or replacing data acquisition and information management practices once based on physical measurements and storage and display in large-format print media. Many agencies must deal with legacy data while avoiding obsolescence in their management practices. Typically, fragmented DOT business practices and the decades-long processes of asset development and life-cycle service have produced disparate data sets that are poorly suited to effective long-term system asset and risk management (2, 8, 9).

## The State of Risk Based Asset Management Implementation

MAP-21 requires that each state must have a risk-based TAM plan in place to preserve the condition of its assets and improve the performance of the National Highway System. Many requirements of MAP-21, including requirements for state DOTs to develop risk-based asset management plans and to establish performance-based planning processes, remain unaffected with the passage of the Fixing America’s Surface Transportation (FAST) Act, signed into law in 2015. However, the state of the practice for U.S. transportation agencies’ use of enterprise risk management is still emergent and evolving. Although agency officials informally manage risks constantly, there are few examples of formal, documented enterprise risk management among U.S. transportation agencies (10). An NCHRP report released in 2016 to identify and evaluate successful implementation of enterprise risk management programs among state DOTs, international transportation agencies, and non-transportation organizations found that a majority of state DOTs did not have a formal risk management process compared to their international transportation and non-transportation counterparts that were surveyed (11). In a 2017 national scan of how state DOTs were integrating risk management in their TAM, it was found that most agencies were using risk registers for their risk management (12). It did not allude to any identification of data or data gaps for updating the risk registers or how that translates to program development or overall decision making. However, it also found that state DOTs were putting in place policies and structures for risk management and the only thing missing was a working implementation for risk-based TAMP to drive decision-making.

In addition, a literature review of the TAMP documents uploaded to the AASHTO TAM portal (13) revealed that all the state DOTs stopped at risk registers identified through workshops with internal and external stakeholders but that process was not integrated with TAM and some did not factor in external events in their risk management. In other words, these initial TAMP documents acknowledged risks but did not address, for the most part, how the risk management process is fully integrated into the overall TAMP.

In the previous chapter, the foundation was laid for the need for a risk management database as the missing piece to full implementation of the risk management framework required to satisfy the intent of the MAP-21 act. In this chapter, the focus is on the implementation of the risk management database using Iowa DOT data and risk register. In addition, this chapter will include discussions on how to expand this approach to be used by any state DOT.

## Implementation Overview

Figure 4.1 is a summary of the implementation process. It begins with data elicitation that identifies what risk events are of interest to the agency, the assets being considered, and the sources of available data. This is followed by data integration which involves spatial integration for data sources with spatial information and non-spatial data integration for data sources that can be linked by a unique identifier. Finally, this results in a risk management database that provides the basis for mapping or visualization and further analyzes. The arrows in the diagram represents the application programming interface (API) that translates one process to the other.

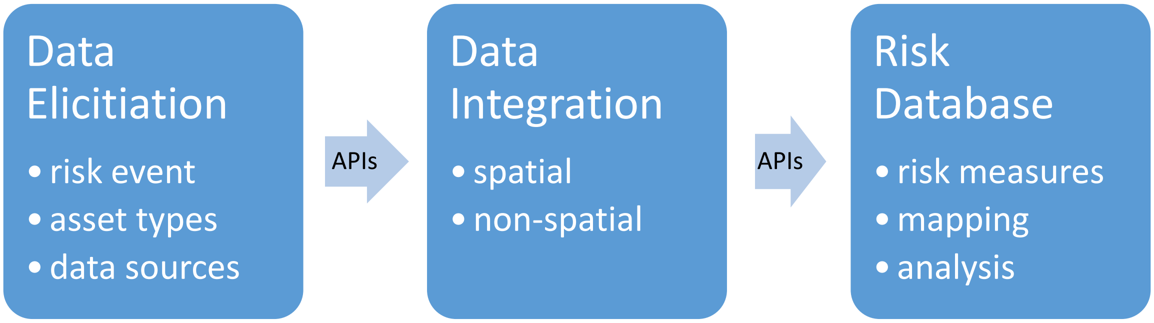


Figure 4.1 Implementation process

In the following sub-sections, each process will be broken down.

### Data Elicitation

This is the process of identifying what risk events the agencies are interested in including in their risk registers along with the critical asset types and data sources. From the previous chapter, it was proposed that the risk register workshop should be improved upon to include the process for providing the inputs for a successful risk management database. Hence, risk registers from TAMP documents submitted by agencies per MAP-21 requirements on the AASHTO portal were reviewed to gauge common risks that agencies have identified (13). The following are the common risk events categories identified by the state DOTs TAMP:

- Financial risks related to the long-term stability of asset management programs
- Information and decision risks related to the implementation of asset management programs

- External risks involving both human-induced and naturally occurring threats
- Asset Condition  risks associated with asset failure

**Financial Risk**

Financial risks are risks related to the long-term stability of asset management programs such as unmet needs in long term budgets, funding stability, and exposure to financial losses by the state DOTs. Table 1 summarizes the sources of the financial risk as explicitly identified in the agencies' TAMP documents. The top three financial risk sources from Table 4.1 are revenue variation or uncertainty, federal funding, and inflation. The biggest driver for revenue variations were attributed to increased fuel efficiency from newer electric and hybrid cars and from decreases in vehicle miles travelled as a result of rural to urban migration. Some agencies like Iowa DOT identified in their risk register that a 15% or more drop in revenue will lead to dropping some of their asset management projects while for Montana, a decrease of more than 3% in revenue will alter their TAM programming. For simplicity, these top 3 financial sources will be used in estimating a financial risk measure as they are readily available. Past revenue from each state is available as well as forecasted revenue from the state DOTs budget office. Federal aid funding information is readily available from US DOT, and inflation numbers are also available from the Federal Reserve.

Financial metrics are not commonly used by U.S. state DOTs compared to their international counterparts in Europe and Australia, and also compared to private sector businesses. These metrics provide transparency and are useful as another set of tools for risk tracking and ensuring that the investment strategies of states DOTs are adequate in the face of risk events (14). The FHWA proposed in 2012 the asset sustainability ratio or index as a simple measure that provides decision makers a comparative idea of the level to which assets are sufficiently funded to reach a desired condition target (14,15). The sustainability index or the financial risk measure (FRM) is calculated thus:

$$\text{FRM} = \frac{amount\ budgeted}{amount\ needed} \qquad (1)$$

To add credibility to the calculation while still keeping it simple, an inflation term will be added to the equation above to yield a new FRM thus

$$\text{FRM} = \frac{amount\ budgeted}{amount\ needed} * (1 - g) \qquad (2)$$

where g = inflation in decimal.

Table 4.1  Summary of financial risks

| **Financial risk source** | **Agency Count** |
|---|---:|
| Revenue variations/uncertainties | 22 |
| Federal funding/ new mandates | 14 |
| Inflation | 8 |
| Unfunded maintenance requirements – e.g., regulatory | 7 |
| Construction costs | 6 |
| Climate change | 5 |
| Public perception/support | 5 |
| Uneven age distribution | 1 |
| Debt servicing | 1 |

A ratio of 1 means that there are no funding gaps which implies that the level of funding is sufficient to meet the set condition target. It is not expected that the ratio from Equation 1 will be more than one but in the event it happens, it should be made equal to one. They further proposed that for one asset, the metric will be called a sustainability ratio and if a class of assets are measured it will be referred to as a sustainability index (15). For the purpose of this study, only pavements will be considered, hence, a sustainability index.

Since the FRM is a network measure, to calculate a risk probability at the analysis segmentation or aggregation level, which in this case is the highway corridor, the FRM will be weighted by the last measured condition of the corridor, VMT carried by the segment, and the system of the segment, that is, if the corridor carries an interstate, US, or state route. The highway corridor can be defined by the state agencies based on traffic volume, freight corridors, population density, or land use. This will lead to a risk probability (financial) calculation, $P_{Finance,}$ thus

$$P_{Finance} = (1 - FRM) * c * s * \frac{VMT\ Corridor}{VMT\ Network} \quad (3)$$

where s = system weight and c = condition weight, and the values for c derived from Table 4.2 based on condition of corridor.

$$s = \frac{VMT\ System}{VMT\ Network} \qquad (4)$$

Table 4.2 Condition weight table

| **Condition** | **Weight** |
|---|---:|
| Good | 1 |
| Fair | 2 |
| Poor | 3 |

### Information and Decision Risk

Information and decision risk is related to the implementation of the asset management program such as lack of critical asset information, quality of data, modeling or forecasting tools for decision making. Risk management is data intensive as a variety of asset management functions within transportation agencies produce, process and analyze substantial amount of data daily (8,9). With the rapid evolution in data and information technologies, transportation agencies are cashing in on the promise of data driven decision-making. The size and complexity of the data are growing over time with challenging implications as agencies seek to ensure that the transportation system delivers high performance and the agency functions effectively and efficiently (9). Extensive lists of IT challenges and data issues are documented in the literature (9, 16, 17). From the TAMP document submitted by the state DOTs, the following are the biggest issues that the agencies explicitly identified as driving the information and decision-related risk:

- the availability and quality of data
- data management system
- inability of the IT department to support decision and analysis of business needs
- performance models not factoring in climate change and other relevant variables that indirectly impact performance and operations
- lack of performance and forecasting models

Another driver of this risk that was not stated in the TAMP documents is the fact that fragmented DOT business practices and the decades-long processes of asset development and life-cycle service have produced disparate data sets that are not well suited for effective long-term system asset and performance management. To remedy the situation, AASHTO has developed a set of Core Data Principles for transportation data (18) in addition to an official data self-assessment guide that includes data management modules with emphasis on quality data, association with strategic goals, regular audits of data, well-defined organizational roles, and mechanisms for security and privacy (9). To qualitatively understand the degree to which their data processes may be at risk, state DOTs can submit to the self-assessment guide, however, for the purpose of the risk management database, the analysis of variances between results and expected targets can become an excellent source of risk information, as it helps to explain performances that are changing suddenly (19) which can be an indication of the inconsistencies in the data. Thus, the consistency of all the variables that are used in the performance estimation must be evaluated to determine the validity and quality of the data before the performance is calculated (20). Hence, the risk probability of information and decision-related risk event is developed to quantify the impact of the data quality and performance or forecasting model. An agency can evaluate its performance or forecasting model by looking at how well the model is predicting new values from data collection based on a target confidence interval. Therefore the risk probability becomes a measure of the ratio of correction predictions, given a confidence interval, compared to the entire network.

$$P_{IDR} = \frac{CP}{NC} \qquad (5)$$

where CP = correct predictions and NC = total number of corridors in the network.

### External Risks

These are risks involving both human-induced and naturally occurring threats such as climatic or seismic events, slope failures, rock falls, lightning strikes, winter weather operations, and terrorism. Natural events such as floods, fire, and earthquakes are unpredictable and have the potential to cause extensive damage, undermining transportation systems, and in some cases severing vital links in the highway network leading to significant holdup to commute, commerce, and potentially to emergency services. Extreme weather events impact nearly every state in the U.S. In 2012, a total of 133 disaster events occurred resulting in about $881 billion in damages (21). There is strong evidence to suggest that events related to climate change such as increasing temperature, heavy precipitation, and coastal flooding will continue to grow in frequency and severity in the coming decades (22, 23, 24, 25). Table 4.3 is a revised summary of the risk events that state DOTs identified in their TAMP documents from the previous chapter and it shows that external events is one of the biggest risk events impacting agencies abilities to deliver on their financial and investment strategies.

A standard set of risk events provide a common basis for risk assessment, which can then be applied to local and regional conditions during a transportation risk analysis (26). For example, earthquakes would not be considered for risk management in Iowa as it is extremely unlikely for the region. Equation 6 shows the general form of a single functional equation for a variable, Y that is a function of *N* parameters. In reality, the systems described will have many variables and will need several functional relationships to be satisfied. However, for simplicity, the systems will be defined by their frequency of occurrence.

$$Y = f(X_1 + X_2 + X_3 + \ldots + X_N) \qquad (6)$$

where N = number of external risk events identified by agencies and X is the frequency of occurrence.

Based on a 2013 Florida DOT study (27), it can be assumed that number of external events follows a Poisson distribution

$$P = e^{-\lambda} \frac{\lambda^k}{k!} \qquad (7)$$

where P is the probability that k number of events will occur per interval of time and λ is the event rate. The recurrence time between two consecutive events can be expressed in a probability distribution function of T, such that:

$$X_T(t) = P(T <= t) = 1 - e^{-\lambda t} \qquad (8)$$

where λ = average rate or number of occurrence per year, and the average recurrence time = 1/λ (27).

The average number of events can be obtained from historic data kept by the agency or from an external national agency.

Table 4.3  Revised summary of risk events

| **Risk Events** | **Agency Count** |
|---|---|
| Financial Risks | 21 |
| Business operations risks (personnel changes and knowledge gap) | 21 |
| External Event | 20 |
| Information and decision risks | 18 |
| Bridge failure – structural, other than hits, scour, resulting in loss of service | 13 |
| Condition related risks/Performance related risks | 13 |
| Heavy truck volume growth/weight increase | 9 |
| Bridges are damaged or destroyed due to scour | 7 |
| ITS or traffic control failure – resulting in safety impact | 6 |
| Scope growth/growth in size of network relative to funding | 6 |
| Culverts and other drainage facilities fail (blockages or overtopping) unexpectedly. | 6 |
| Capacity improvements projects are delayed/deferred maintenance | 5 |
| Retaining walls (requiring maintenance but no mobility impacts)/slope failure | 4 |
| Bubble in asset replacement needs due to uneven asset age distribution | 4 |
| Negative Public opinion/public involvement delay killing projects | 4 |
| Sinkholes emerge under or near roadway sections compromising foundation. | 3 |
| Winter weather treatments and impacts on pavement deterioration | 3 |
| Socioeconomic risks- population growth/ shift to urban areas/land use | 3 |
| Avalanche requiring maintenance but no/minimal delay | 2 |
| Travel Mode changes | 2 |
| Highway safety | 2 |
| Tunnel collapse/closure due to safety incident | 1 |
| Subsurface utilities impacts by others in ROW (and below roadways) | 1 |
| Make projects more complex | 1 |

For rare events, where there is an effective small sample size or no data, the estimation of a probability of occurrence will benefit from the introduction of a small a priori probability utilizing Bayesian networks (28).

### Asset Condition Risk

Asset condition risks are associated with asset failure such as structural, capacity or utilization, reliability of performance, aging, soil and subsurface utilities, and maintenance or operation. According to NCHRP Report 08-93, failure is not only "acute and complete, but also as incremental failure including:

- Structural: where the physical condition of the asset is the measure of deterioration, service potential or remaining life;
- Capacity/utilization: where it is necessary to understand the degree to which an asset is under-or-over-utilized compared to the desired level of service;
- Level of service failures: where reliability or performance targets cannot be met;
- Obsolescence: when technological change or lack of replacement parts render the asset uneconomic to operate;
- Cost or economic impact: where the cost to maintain and operate an asset is likely to exceed the economic return expected, or is more than the customer is willing to pay."

Before MAP–21, there was no explicit mandate for state DOTs to show how their TAMP maintained national performance outcomes. There was no requirement to track condition or performance, set up targets, measure progress toward targets, or report on condition or performance in a manner that FHWA could use to evaluate the entire system. This final MAP-21 rule creates performance measures to assess pavement and bridge conditions on the NHS for the purpose of achieving consistent national performance outcomes. The four pavement performance measures are (29):

- percentage of pavements on the interstate system in good condition
- percentage of pavements on the interstate system in poor condition
- percentage of pavements on the NHS (excluding the interstate system) in good condition; and percentage of pavements on the NHS (excluding the interstate system) in poor condition.

The two performance measures for assessing bridge condition are:

- percentage of NHS bridges classified as in good condition; and
- percentage of NHS bridges classified as in poor condition

At the network level, a set of measures that evaluate both condition and risk are ones that predict the percentage of assets that meet the targets defined by MAP-21 into the future based on anticipated funding levels (14). To capture this risk at the corridor level, the percentage of assets that meet the targets will be weighted by the rate of deterioration of the corridor. Also, this can be accomplished by weighting it with one or more of these variables that drive pavement deterioration such as heavy truck traffic growth on the corridor segment, maintenance history, and winter weather operations to capture some of climate risk factor.

### Risk Consequences

The goal of risk analysis is to identify the various elements of risk and combining them into some quantifiable estimate of risk. The intent of this research is to provide that estimate of risk in monetary terms. Equation 8 is the basic formula for calculating risk, R:

$$R = C * T \qquad (8)$$

Where R and C (consequences) is measured in dollars and T (threat) is expressed as probability (26). Since transportation networks are usually broken into corridors for planning purposes, the importance of each corridor then becomes a function of the traffic it carries, the urban centers it connects, and the development that it drives. Breaking out the consequences terms in Equation 8 will result in the following formula (26):

$$C = \text{human impact (fatalities + injuries) + user cost (vehicle running cost + lost wages) + owner cost (asset damage + asset loss)} + \text{impact}_1 + \text{impact}_2 + \ldots + \text{impact}_n \qquad (9)$$

The value of human life and serious injury is calculated by each state DOT. Owner costs are the replacement value of each asset. Vehicle running costs can be determined from the federal allowable rates (30). User wage costs are available from National Occupational Employment and Wage Estimates (*31*). Vehicle occupancy rates are available from the National Household Travel Survey (*32*). Equation 9 can be modified to add additional variables such as the value of goods carried on the corridor. Value of goods carried by the corridor can be obtained from FHWA Freight Analysis Framework, FAF (33). Obtaining the data required for calculating the risk consequences will require the integration of data not captured by the state DOTs such as socio-economic data from US Census Bureau.

## Data Integration

Effective and efficient risk management relies heavily on availability of objective data. The data required to run complex risk analysis resides in multiple systems across the state DOTs departments and in different schemas. The difficulty associated with organization and normalization often presents the biggest challenge in receiving relevant and timely risk information. Tactical database and spreadsheet tools are inflexible, difficult to maintain and generally unreliable. The lack of integration between systems poses big challenges to transportation agencies' efforts to integrate risk management in their TAM. However, since data collection is capital intensive, the aim of the risk database framework is not to force agencies into a specific data management system but instead using the existing agencies DOT enterprise data systems.

Accomplishing this integration requires a spatial and non-spatial approach (Figure 4.2) to integration of available inventory, measurement, reporting, and financial planning data. These two approaches are discussed in the following sub-sections.

### Spatial Integration

A key characteristic of spatial data is reflective of the technologies that are used to collect them, technologies such as global positioning systems (GPS) and remote sensing (8, 25). With rapid evolution in these technologies, the accuracy of the positional location of the data collection has greatly improved especially for the level of accuracy required for state DOTs decision making. In general, state DOTs employ the following three methods of location referencing as culled from NCHRP Research Report 903 (34):

- 1-D location referenced to a known location, such as a mile point or offset point from stationing;
- 2-D shape with X and Y lateral dimensions, similar polygon outline on a plan view; and
- 3-D extent that incorporates an elevation (z-dimension).

Another consideration of spatial integration is how data collection is encapsulated using GIS data models such as vector and raster data models as shown in Figure 4.3. For instance, in pavement management, condition data collection intervals are often standardized at 1/100th of a mile. Hence, the data is then aggregated to pavement management analysis segment that can

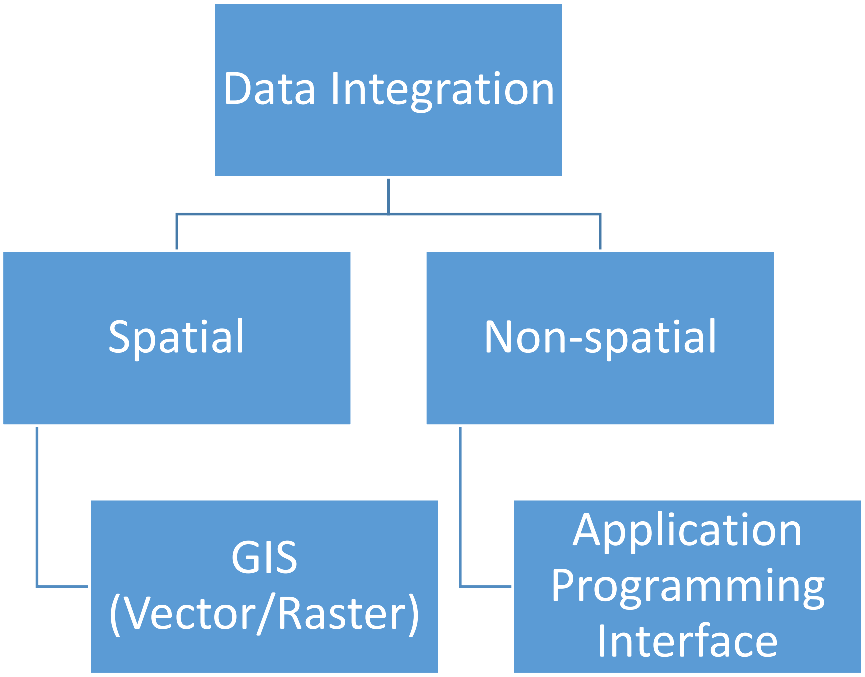


Figure 4.2  Data integration approach

range from one to several miles. For an ambitious project such as a risk management database, the data will invariably come in various geographic extents requiring a combination of the locational referencing methods as well as spatial data assignment in a GIS environment.  From the NCHRP Report on *Successful Practices in GIS-Based Asset Managements*, GIS facilitates "the integration of disparate data entities using location as the common denominator, visualization of multiple data layers for a selected area or network location, map-based data access for viewing and editing, and spatial analysis involving queries of information based on proximity, route, or geospatial feature." (8) Hence, GIS can take the various data entities whether modeled as point, line, or polygon feature and transforms the data using spatial relationship functions to produce a resulting dataset that aggregates the desired spatial outcomes as shown in Figure 4.4. The resulting dataset then has all the variables required for estimating the risk measures discussed in the preceding sections.

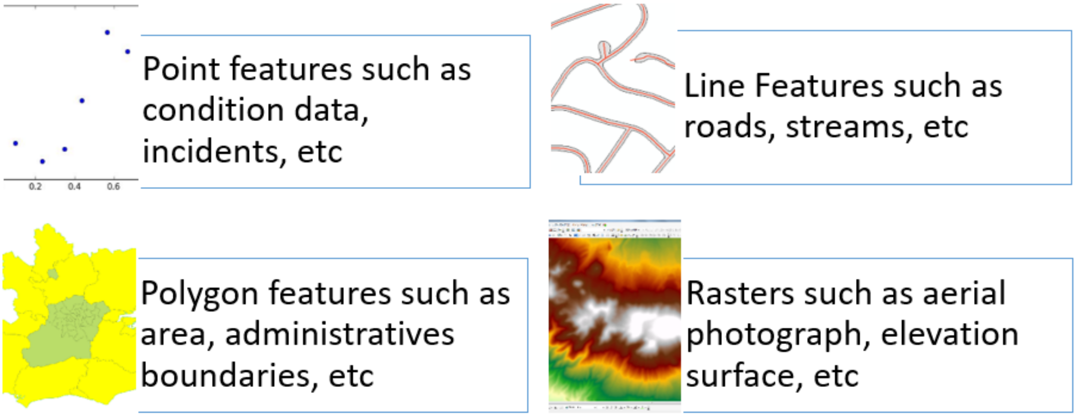


Figure 4.3 GIS feature types

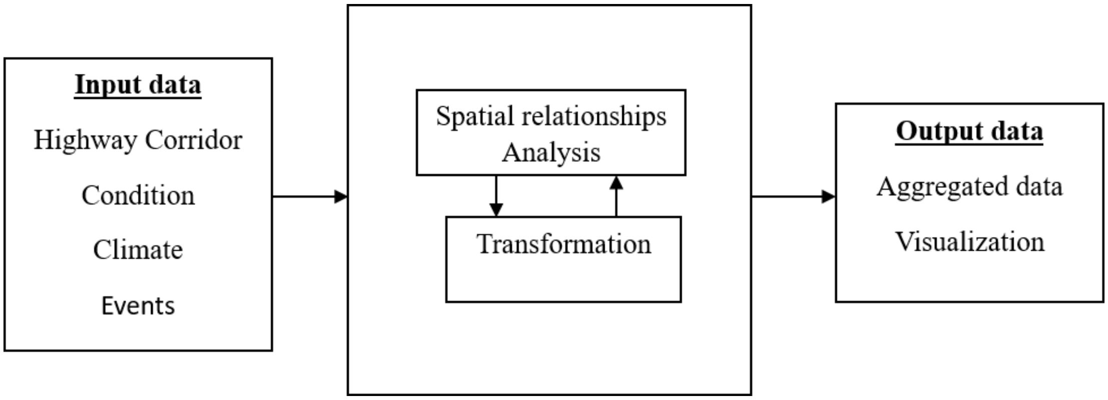


Figure 4.4 Data integration work flow

## Non-Spatial Integration

From Figure 4.4, the input data are usually disparate data entities. While a GIS application can integrate these data by virtue of their spatial location, it does employ a tightly coupled system architecture which implies that the input must be predefined. However, these input data, especially for a risk management database, can come from sources outside of the agency or could be legacy systems within the state DOT that would require a fair amount of data pre-processing before it can be input into the GIS application. This data pre-processing is where the non-spatial data integration comes in to get the data into a format that it can be consumed by the GIS application with the desired outcomes. In a technical sense, this is the functionality of an application programming interface, API. APIs are employed in software engineering to define permissible inputs, outputs, and controls. It is basically a set of specifications that define how disparate elements can communicate with each other (35, 36). In this risk database implementation, the API is used to prepare inputs into the GIS module as well as to package the output for integration with other analytical tools for knowledge discovery to support the decision-making. Hence, Figure 4.4 becomes modified by the addition of the API to result in Figure 4.5. The inclusion of the API enables the overall application to be packaged into an extensible single standalone program with plugin for other analytical tools or third party visualization package. In addition, it minimizes the learning curve for state DOT risk manager by hiding all the complex programming using the API. In addition, to minimizing the learning curve, it also allows for easy updates and addition of new functionalities.

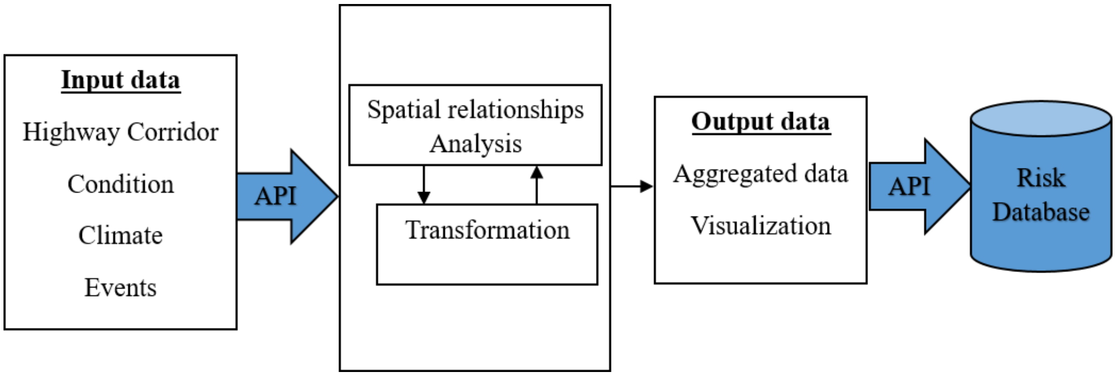


Figure 4.5  Data integration workflow showing the API

### The Risk Database

The risk database is populated by the following information as discussed in Chapter 3:

- Risk Identification Number- ties all corridors with the same risk as well as track risk dependencies
- Brief explanation of the risk
- Asset inventory- number and type of assets on the corridor

- Condition of assets based on agreed upon performance measures
- Environmental level data- physical attributes, proximity to watershed, geographic properties, soil type, etc.
- Socio-economic indicators- population, land use, traffic volume
- Probability value- probability or likelihood of the risk occurring, estimated during the risk calculation stage of the data integration framework
- Risk measures- based on the elicitation stage and determined during the risk calculation stage
- Impact measure- impact of the risk in monetary terms value determined during the risk calculation stage
- Area of impact- estimated as a function of the geographic area as well as the socio-economic markers near the corridor
- Severity of the risk event- function of the area of impact
- Ranking of each individual risk within the corridor, similar to Figure 3.3. Ranked risks are those with a high severity and high consequence within the corridor
- Total risk on the corridor- weighted sum of all the risks in the corridor
- Risk monitor- indicates if the risk has increased, remained the same or decreased in severity since last available data collection
- Risk owner- which agency is responsible for the risk
- Risk mitigation plans- based on risk management and data elicitation workshop
- Risk status- indicates whether the risk is active or whether it has been mitigated
- Risk potential- indicates whether the risk can lead to other risk and the potential for a cascade effect

These are spread out over several database tables as shown in Figure 4.6. The number of database tables depends on how many external events that the state DOT identifies in its risk elicitation process. Each table is populated following the results of the spatial integration and can be populated by data from various input sources. For example, the financial risk table is populated from the highway corridor inventory data, as well as the financial/business operations data. The role of the API in Figure 4.5 is to map each table with the relevant fields from the aggregated data.

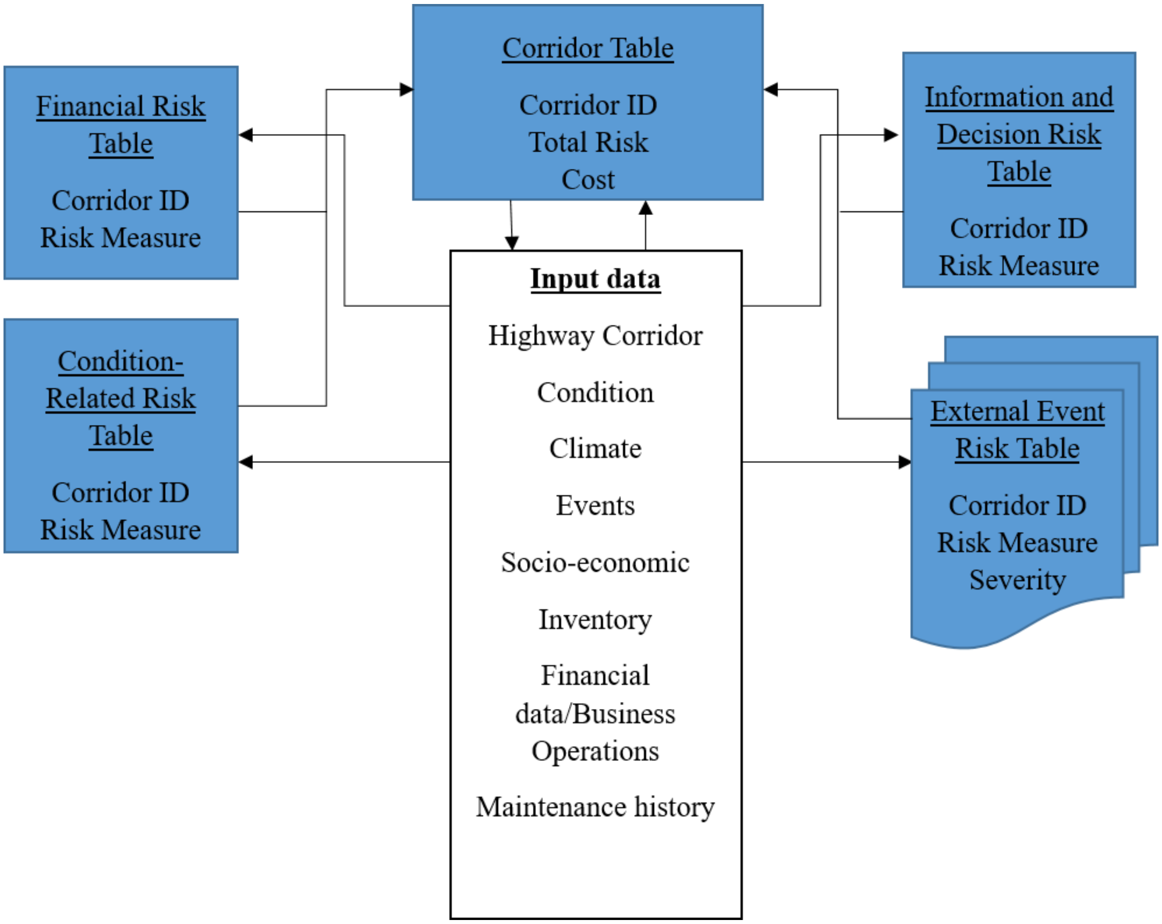


Figure 4.6 Risk database model

Figure 4.7 shows a flowchart of how an agency can implement the proposed database integration framework. It begins from a very collaborative workshop whose main goal is to synthesize the risk events, assets, and data needs to be aggregated and how to measure the risk impacts using the identified data as well as the granularity level of the analysis that the agency desires to drive its decision-making.

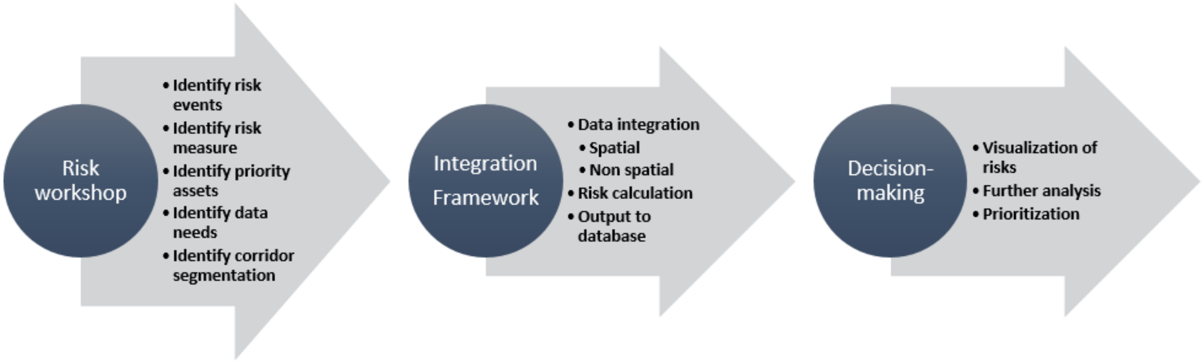


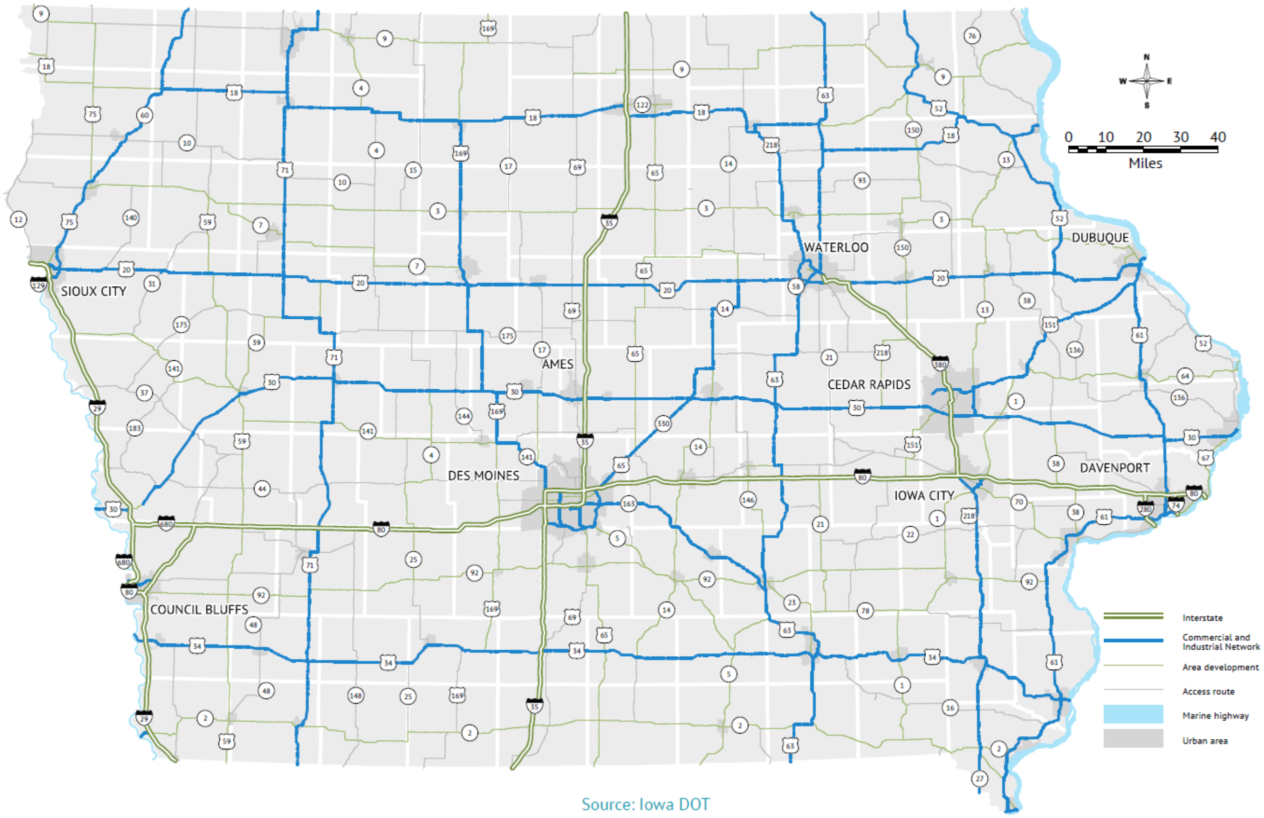
Figure 4.7 Implementation framework for agency

## Risk Management Data Implementation

Demonstration of the risk management database integration framework is implemented using Iowa data on its pavement management program as well as supplementary data. Iowa was chosen based on accessibility and availability of data that could be used to develop a realistic demonstration of the capabilities.

From the NCHRP 800 Report, “the Iowa DOT has an active and mature GIS program and is well placed to leverage a variety of data sources” that can be used for asset management decision support. The department collects and maintains geospatial data sets that can provide additional information that can be tapped for a rich risk management database. Available pavement data include condition data, international roughness index (IRI), rutting, friction, cracking, faulting, and material tests for specific projects. Other available data include traffic, economic drivers, land use, and weather information.

While the network level information is aggregated to planning corridors as shown in Figure 4.8 from the Planning Division, the demonstration illustrates the use of GIS to integrate network- and project-level data that have been identified via the risk identification process to be relevant to the risk management process to produce a risk management database to support trend analysis and pattern detection—and communicate results of these analyses in order to identify appropriate mitigation response.



Source: Iowa DOT

Figure 4.8 Map of Iowa showing the interstate corridors

## Methods and Materials

The data integration framework for populating the risk management database is implemented using two applications namely Feature Manipulation Engine (FME) and ESRI suite of geospatial tools.

### Feature manipulation engine

The Feature Manipulation Engine (FME) is a proprietary product from Safe Software. FME is a data integration and transformation tool for automating data processing workflows. It is the engine responsible for the spatial integration component. It can read and transform data from various popular formats. In addition, even though coding is not required to build the processes, it provides the ability to write programs using Python and R to extend the functionality of the workflow. This is very important as it provides the option of designing the API using inbuilt functionality or using the programming language support to design an efficient process for the API to communicate with the spatial integration module. As a result, FME makes cross-platform development simpler with availability of programming using Python, while allowing developers to create seamless user experiences for the end-users. In addition, it enables declarative data fetching where a client can specify exactly what data it needs from an API. As a result, the API allows for fine-grained insights about the data that is requested on the backend. As each client specifies exactly what information it's interested in, it is possible to gain a deep understanding of how the available data is being used. This can help in evolving an API and deprecating specific fields that are no longer used.

Figure 4.9 shows a generic workflow of how the FME works. In the example, it reads data from two sources A and B and integrates the data into one dataset C via built-in or customized transformation tools appropriate for the data sources and the desired outcomes.

### ESRI tools

While the FME does provide a map display for visualization, it is not built for robust visualization of spatial data as it is for its transformation. Figure 4.10 shows the overlay of all the sample input data from the Iowa demonstration using ESRI's ArcGIS Desktop®. ESRI is the most popular GIS vendor for state DOTs and most state DOTs has one or several of its desktop applications already in use. Like FME, it also comes with programmable GIS functionality for extending its application.

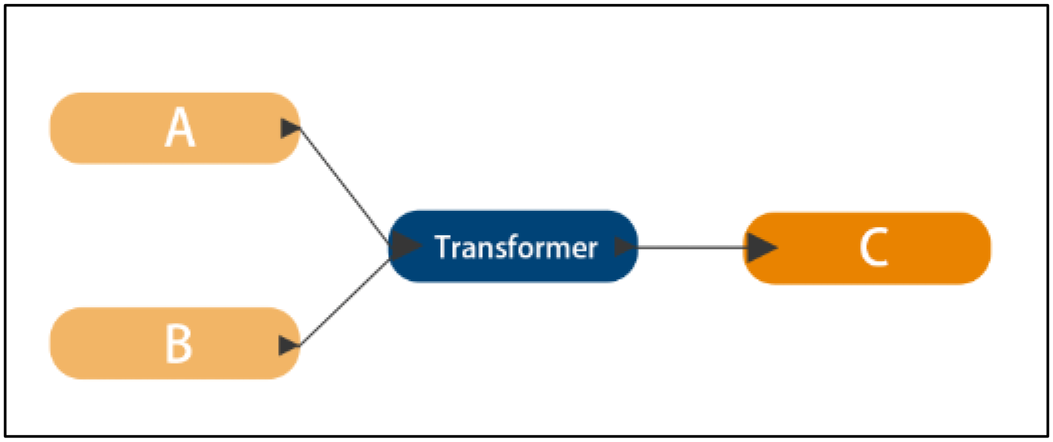


Figure 4.9 Generic FME workflow

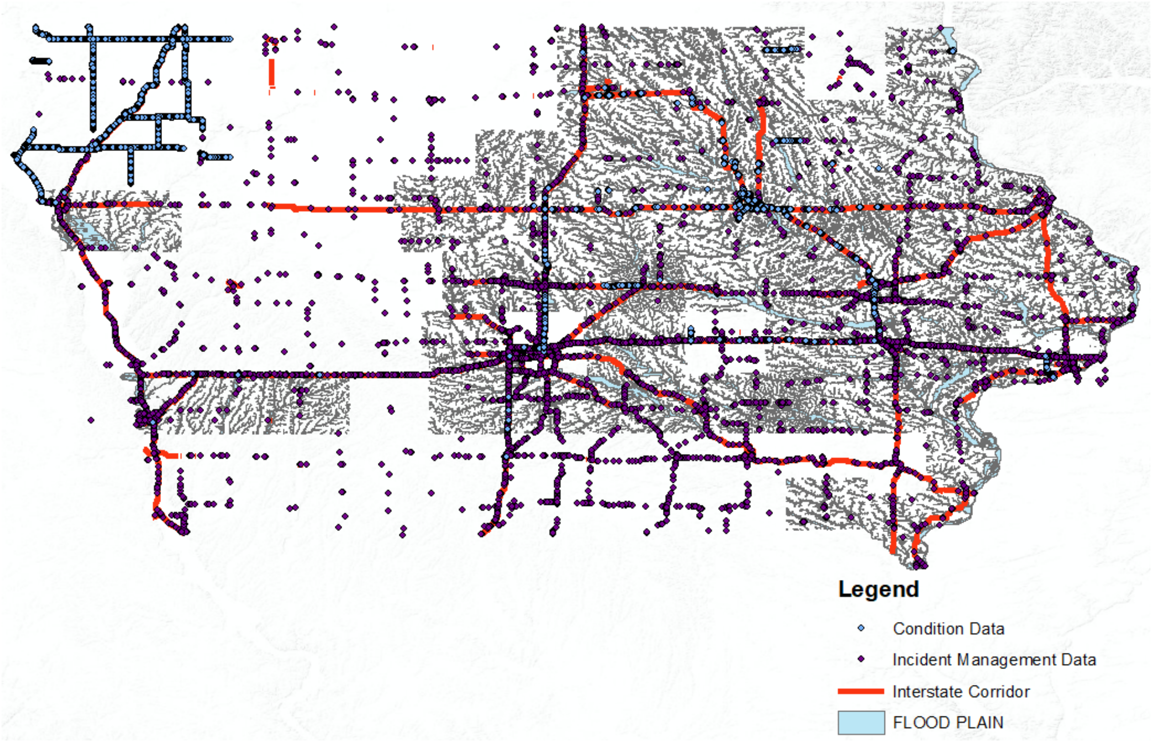


Figure 4.10 Map showing data overlay for select risk data

### Data processing

As with any data from disparate sources and collected for different applications, there is need for data cleaning to streamline the integration process. First and foremost, the data is checked for its data model and metadata that will determine how the data extraction and integration API will be designed. In addition, missing data, incomplete records or invalid data are evaluated as well as the coordinate system of data collection or archival. For example, point data such as events with latitude and longitude information will need to be re-projected to match the coordinate system of the corridor features that is been integrated with to ensure that the points are aggregated to the correct corridor.

Figure 4.11 shows the workflow for the point data sources. The event data is archived using comma-delimited files (CSV) with latitude and longitude fields that is passed through the vertex creator to create points which are then re-projected to match the coordinate system of the corridor as shown. Also, the pavement condition data which are already in points are passed directly to be re-projected. Both streams of data are then integrated to the corridor by spatial assignment. There is a buffer application that ensures that whatever points that gets assigned to the corridor are within 20m. The output of the spatial integration is passed through a filter that enables further quality control/quality assurance to ensure the integrity of the process as shown in Figure 4.12. In Figure 4.12, data passing the filter are then summarized by corridor and then the risk database tables are populated accordingly.

Not all data sources are point data, some are area data such as the weather information from the Iowa Mesonet (37) that breaks the state into geographic grids and climate data is aggregated to these grids. The same overall process as shown in Figures 4.11 and 4.12 will still

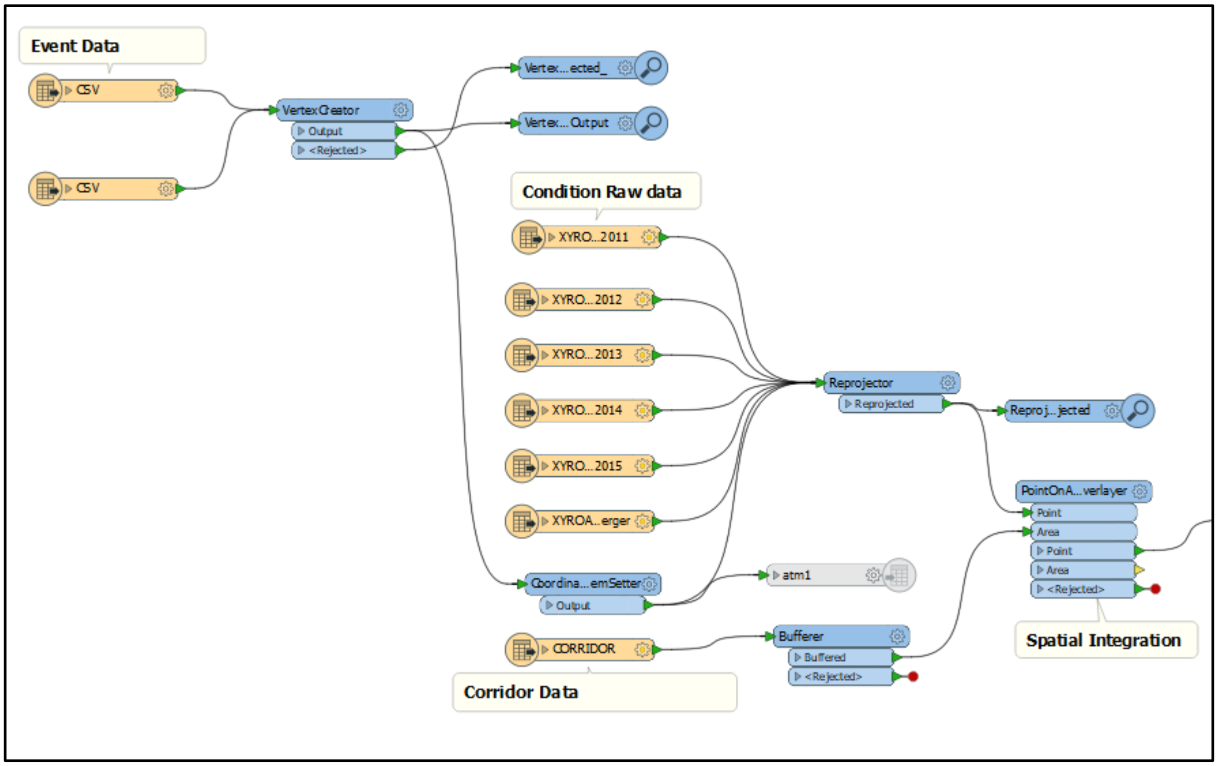


Figure 4.11 Workflow showing data preprocessing

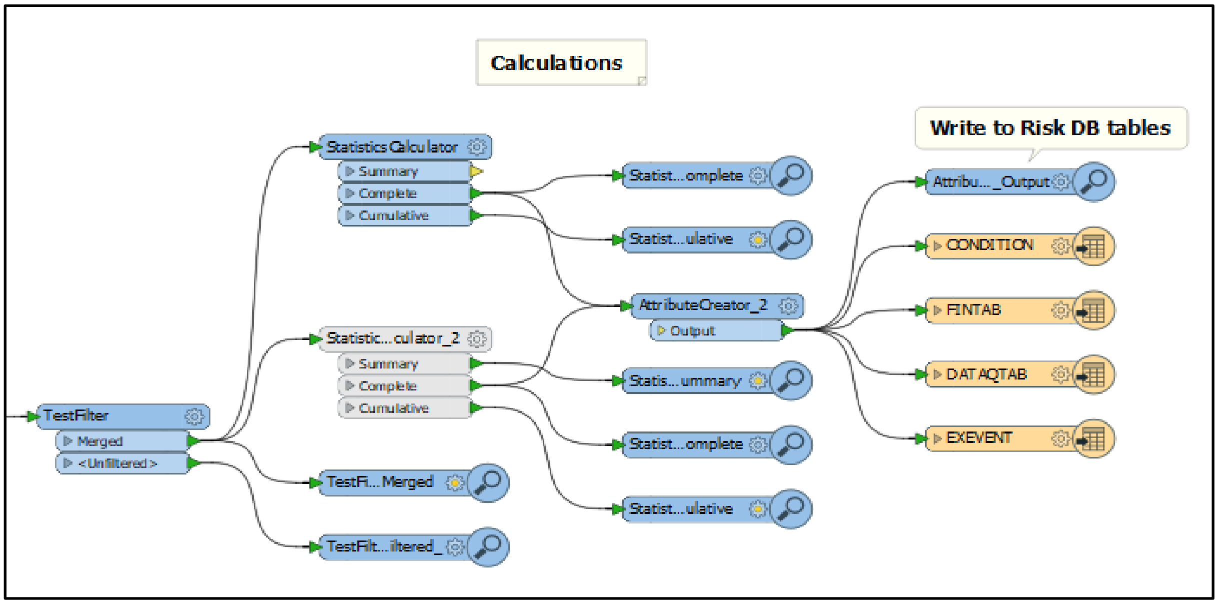
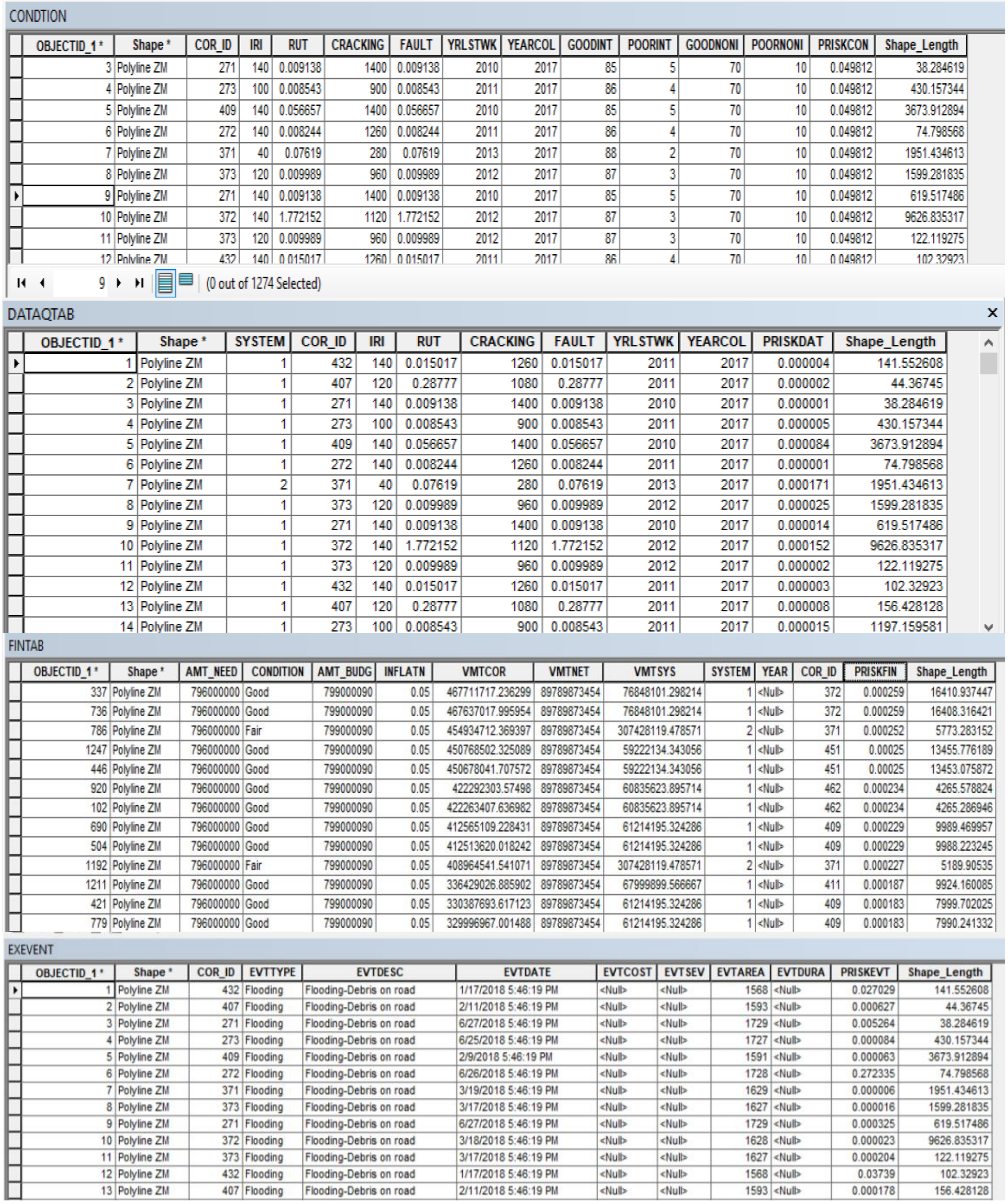


Figure 4.12 Workflow showing data aggregation

apply to their integration with the corridor but with a different spatial assignment protocol that takes into account the areal characteristics.

### Decision making

At the core of the need for a risk management database is to be able to integrate data from various relevant sources and having the results in a form that enables further analysis and decision making. Figure 4.13 shows the results of the data integration with the risk database table



CONDTION

| OBJECTID_1 * | Shape * | COR_ID | IRI | RUT | CRACKING | FAULT | YRLSTWK | YEARCOL | GOODINT | POORINT | GOODNONI | POORNONI | PRISKCON | Shape_Length |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 | Polyline ZM | 271 | 140 | 0.009138 | 1400 | 0.009138 | 2010 | 2017 | 85 | 5 | 70 | 10 | 0.049812 | 38.284619 |
| 4 | Polyline ZM | 273 | 100 | 0.008543 | 900 | 0.008543 | 2011 | 2017 | 86 | 4 | 70 | 10 | 0.049812 | 430.157344 |
| 5 | Polyline ZM | 409 | 140 | 0.056657 | 1400 | 0.056657 | 2010 | 2017 | 85 | 5 | 70 | 10 | 0.049812 | 3673.912894 |
| 6 | Polyline ZM | 272 | 140 | 0.008244 | 1260 | 0.008244 | 2011 | 2017 | 86 | 4 | 70 | 10 | 0.049812 | 74.798568 |
| 7 | Polyline ZM | 371 | 40 | 0.07619 | 280 | 0.07619 | 2013 | 2017 | 88 | 2 | 70 | 10 | 0.049812 | 1951.434613 |
| 8 | Polyline ZM | 373 | 120 | 0.009989 | 960 | 0.009989 | 2012 | 2017 | 87 | 3 | 70 | 10 | 0.049812 | 1599.281835 |
| 9 | Polyline ZM | 271 | 140 | 0.009138 | 1400 | 0.009138 | 2010 | 2017 | 85 | 5 | 70 | 10 | 0.049812 | 619.517486 |
| 10 | Polyline ZM | 372 | 140 | 1.772152 | 1120 | 1.772152 | 2012 | 2017 | 87 | 3 | 70 | 10 | 0.049812 | 9626.835317 |
| 11 | Polyline ZM | 373 | 120 | 0.009989 | 960 | 0.009989 | 2012 | 2017 | 87 | 3 | 70 | 10 | 0.049812 | 122.119275 |
| 12 | Polyline ZM | 432 | 140 | 0.015017 | 1260 | 0.015017 | 2011 | 2017 | 86 | 4 | 70 | 10 | 0.049812 | 102.32923 |

9 (0 out of 1274 Selected)

DATAQTAB

| OBJECTID_1 * | Shape * | SYSTEM | COR_ID | IRI | RUT | CRACKING | FAULT | YRLSTWK | YEARCOL | PRISKDAT | Shape_Length |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Polyline ZM | 1 | 432 | 140 | 0.015017 | 1260 | 0.015017 | 2011 | 2017 | 0.000004 | 141.552608 |
| 2 | Polyline ZM | 1 | 407 | 120 | 0.28777 | 1080 | 0.28777 | 2011 | 2017 | 0.000002 | 44.36745 |
| 3 | Polyline ZM | 1 | 271 | 140 | 0.009138 | 1400 | 0.009138 | 2010 | 2017 | 0.000001 | 38.284619 |
| 4 | Polyline ZM | 1 | 273 | 100 | 0.008543 | 900 | 0.008543 | 2011 | 2017 | 0.000005 | 430.157344 |
| 5 | Polyline ZM | 1 | 409 | 140 | 0.056657 | 1400 | 0.056657 | 2010 | 2017 | 0.000084 | 3673.912894 |
| 6 | Polyline ZM | 1 | 272 | 140 | 0.008244 | 1260 | 0.008244 | 2011 | 2017 | 0.000001 | 74.798568 |
| 7 | Polyline ZM | 2 | 371 | 40 | 0.07619 | 280 | 0.07619 | 2013 | 2017 | 0.000171 | 1951.434613 |
| 8 | Polyline ZM | 1 | 373 | 120 | 0.009989 | 960 | 0.009989 | 2012 | 2017 | 0.000025 | 1599.281835 |
| 9 | Polyline ZM | 1 | 271 | 140 | 0.009138 | 1400 | 0.009138 | 2010 | 2017 | 0.000014 | 619.517486 |
| 10 | Polyline ZM | 1 | 372 | 140 | 1.772152 | 1120 | 1.772152 | 2012 | 2017 | 0.000152 | 9626.835317 |
| 11 | Polyline ZM | 1 | 373 | 120 | 0.009989 | 960 | 0.009989 | 2012 | 2017 | 0.000002 | 122.119275 |
| 12 | Polyline ZM | 1 | 432 | 140 | 0.015017 | 1260 | 0.015017 | 2011 | 2017 | 0.000003 | 102.32923 |
| 13 | Polyline ZM | 1 | 407 | 120 | 0.28777 | 1080 | 0.28777 | 2011 | 2017 | 0.000008 | 156.428128 |
| 14 | Polyline ZM | 1 | 273 | 100 | 0.008543 | 900 | 0.008543 | 2011 | 2017 | 0.000015 | 1197.159581 |

FINTAB

| OBJECTID_1 * | Shape * | AMT_NEED | CONDITION | AMT_BUDG | INFLATN | VMTCOR | VMTNET | VMTSYS | SYSTEM | YEAR | COR_ID | PRISKFIN | Shape_Length |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 337 | Polyline ZM | 796000000 | Good | 799000090 | 0.05 | 467711717.236299 | 89789873454 | 76848101.298214 | 1 | <Null> | 372 | 0.000259 | 16410.937447 |
| 736 | Polyline ZM | 796000000 | Good | 799000090 | 0.05 | 467637017.995954 | 89789873454 | 76848101.298214 | 1 | <Null> | 372 | 0.000259 | 16408.316421 |
| 786 | Polyline ZM | 796000000 | Fair | 799000090 | 0.05 | 454934712.369397 | 89789873454 | 307428119.478571 | 2 | <Null> | 371 | 0.000252 | 5773.283152 |
| 1247 | Polyline ZM | 796000000 | Good | 799000090 | 0.05 | 450768502.325089 | 89789873454 | 59222134.343056 | 1 | <Null> | 451 | 0.00025 | 13455.776189 |
| 446 | Polyline ZM | 796000000 | Good | 799000090 | 0.05 | 450678041.707572 | 89789873454 | 59222134.343056 | 1 | <Null> | 451 | 0.00025 | 13453.075872 |
| 920 | Polyline ZM | 796000000 | Good | 799000090 | 0.05 | 422292303.57498 | 89789873454 | 60835623.895714 | 1 | <Null> | 462 | 0.000234 | 4265.578824 |
| 102 | Polyline ZM | 796000000 | Good | 799000090 | 0.05 | 422263407.636982 | 89789873454 | 60835623.895714 | 1 | <Null> | 462 | 0.000234 | 4265.286946 |
| 690 | Polyline ZM | 796000000 | Good | 799000090 | 0.05 | 412565109.228431 | 89789873454 | 61214195.324286 | 1 | <Null> | 409 | 0.000229 | 9989.469957 |
| 504 | Polyline ZM | 796000000 | Good | 799000090 | 0.05 | 412513620.018242 | 89789873454 | 61214195.324286 | 1 | <Null> | 409 | 0.000229 | 9988.223245 |
| 1192 | Polyline ZM | 796000000 | Fair | 799000090 | 0.05 | 408964541.541071 | 89789873454 | 307428119.478571 | 2 | <Null> | 371 | 0.000227 | 5189.90535 |
| 1211 | Polyline ZM | 796000000 | Good | 799000090 | 0.05 | 336429026.885902 | 89789873454 | 67999899.566667 | 1 | <Null> | 411 | 0.000187 | 9924.160085 |
| 421 | Polyline ZM | 796000000 | Good | 799000090 | 0.05 | 330387693.617123 | 89789873454 | 61214195.324286 | 1 | <Null> | 409 | 0.000183 | 7999.702025 |
| 779 | Polyline ZM | 796000000 | Good | 799000090 | 0.05 | 329996967.001488 | 89789873454 | 61214195.324286 | 1 | <Null> | 409 | 0.000183 | 7990.241332 |

EXEVENT

| OBJECTID_1 * | Shape * | COR_ID | EVTTYPE | EVTDESC | EVTDATE | EVTCOST | EVTSEV | EVTAREA | EVTDURA | PRISKEVT | Shape_Length |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Polyline ZM | 432 | Flooding | Flooding-Debris on road | 1/17/2018 5:46:19 PM | <Null> | <Null> | 1568 | <Null> | 0.027029 | 141.552608 |
| 2 | Polyline ZM | 407 | Flooding | Flooding-Debris on road | 2/11/2018 5:46:19 PM | <Null> | <Null> | 1593 | <Null> | 0.000627 | 44.36745 |
| 3 | Polyline ZM | 271 | Flooding | Flooding-Debris on road | 6/27/2018 5:46:19 PM | <Null> | <Null> | 1729 | <Null> | 0.005264 | 38.284619 |
| 4 | Polyline ZM | 273 | Flooding | Flooding-Debris on road | 6/25/2018 5:46:19 PM | <Null> | <Null> | 1727 | <Null> | 0.000084 | 430.157344 |
| 5 | Polyline ZM | 409 | Flooding | Flooding-Debris on road | 2/9/2018 5:46:19 PM | <Null> | <Null> | 1591 | <Null> | 0.000063 | 3673.912894 |
| 6 | Polyline ZM | 272 | Flooding | Flooding-Debris on road | 6/26/2018 5:46:19 PM | <Null> | <Null> | 1728 | <Null> | 0.272335 | 74.798568 |
| 7 | Polyline ZM | 371 | Flooding | Flooding-Debris on road | 3/19/2018 5:46:19 PM | <Null> | <Null> | 1629 | <Null> | 0.000006 | 1951.434613 |
| 8 | Polyline ZM | 373 | Flooding | Flooding-Debris on road | 3/17/2018 5:46:19 PM | <Null> | <Null> | 1627 | <Null> | 0.000016 | 1599.281835 |
| 9 | Polyline ZM | 271 | Flooding | Flooding-Debris on road | 6/27/2018 5:46:19 PM | <Null> | <Null> | 1729 | <Null> | 0.000325 | 619.517486 |
| 10 | Polyline ZM | 372 | Flooding | Flooding-Debris on road | 3/18/2018 5:46:19 PM | <Null> | <Null> | 1628 | <Null> | 0.000023 | 9626.835317 |
| 11 | Polyline ZM | 373 | Flooding | Flooding-Debris on road | 3/17/2018 5:46:19 PM | <Null> | <Null> | 1627 | <Null> | 0.000204 | 122.119275 |
| 12 | Polyline ZM | 432 | Flooding | Flooding-Debris on road | 1/17/2018 5:46:19 PM | <Null> | <Null> | 1568 | <Null> | 0.03739 | 102.32923 |
| 13 | Polyline ZM | 407 | Flooding | Flooding-Debris on road | 2/11/2018 5:46:19 PM | <Null> | <Null> | 1593 | <Null> | 0.000178 | 156.428128 |

Figure 4.13  Risk database showing sample values

populated with sample values. The risk data base in this demonstration is a file geodatabase. A file geodatabase is an ESRI proprietary database that provides all the functionality of an object relational database for spatial as well as non-spatial attributes. Additional tables can be synthesized based on any desired outcome.

The integration of historical and current data can be an effective tool to understanding past and existing system performance. The results can be very important for analyzing the causes of asset failures and in understanding the spatial and temporal dynamics of such in order to help prioritize the types of risks identified. This can be very useful for developing a quantitative measurement of risk that can go a long way to help track, monitor, and continuously update evolving risk registers for state DOTs.

In addition, the data can be used to create a benchmark of asset performance as a very useful tool for understanding the impacts of the identified risks. In fact, using the available data to track for the identified risks is the essence of risk analysis. Statistical tools can then be employed to assess expected performance of the transportation system under different risk scenarios. Figure 4.14 shows how the results of the data integration can be used for decision-making. Figure 4.14 presents a categorical way of presenting quantitative data to show areas of interest on the I-80 corridor. These are areas of high impact to freight travel should any risk event take place on those corridors shown in red. Additional maps can be produced based on all the underlying datasets that have been integrated to show what is driving the issue providing decision-makers with options in their risk mitigation approaches and the benefit-cost implications of each option.

Within the context of risk-based TAMP, leveraging available data and analysis tools helps visualize and articulate, in both qualitative and quantitative terms, how the combination of various risks and mitigation strategies would impact performance targets. It paves the way for the consideration of how various factors, such as revenue constraints, demographic trends, economic shifts or technological innovation can affect a state or region and its transportation system performance (38).

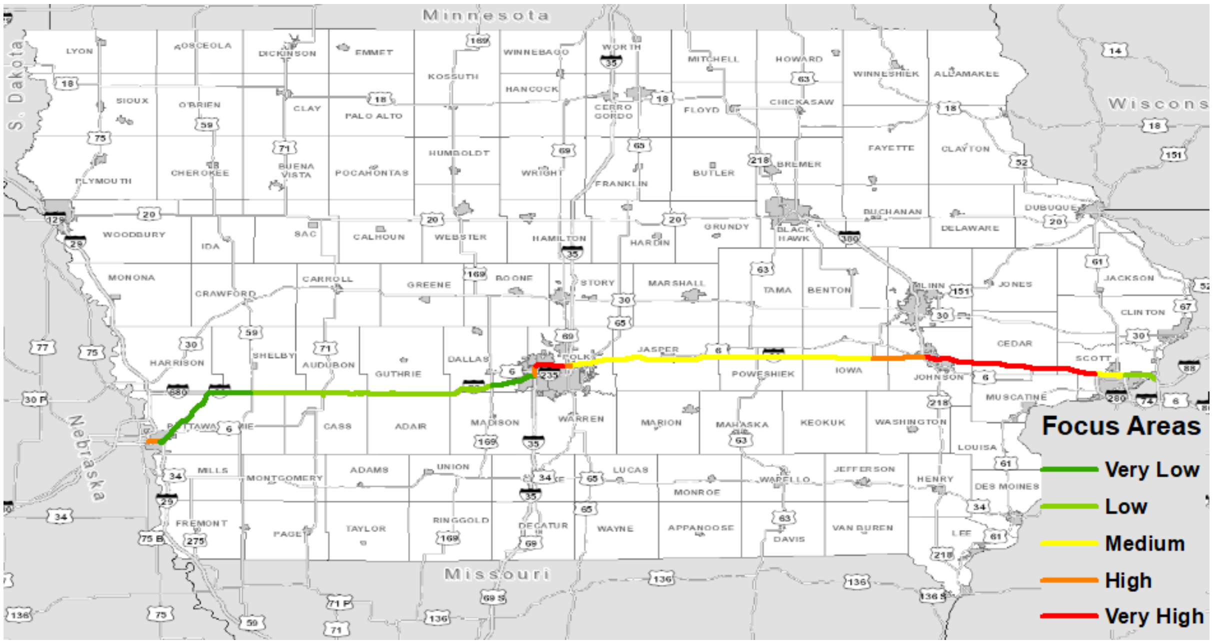


Figure 4.14 The Iowa Interstate 80 corridor freight capacity

### Conclusion

Rapid evolution of data and information technologies present both opportunities and challenges as agencies seek to ensure that the transportation system continues to perform effectively and efficiently. In addition, many agencies must deal with legacy data while avoiding the loss of continuity in their management practices. Usually, disparate DOT business practices and the decades-long processes of asset development and life-cycle services have produced varied datasets that need data integration for effective risk management.

Although most state DOTs have included a risk register in their TAMP very little was found on how it will be used for decision making. Therefore, since documentation of agencies risks was required as part of MAP-21 a risk management database system was implemented. This database will improve the still emergent risk management methodology among state DOTs. It provides a tool by which the risks within the agency can be effectively visualized and managed as part of the ongoing process of risk-based TAMP.

The design of the risk management database provides a way for risks identified by the agency to be easily added, updated, and modified irrespective of its spatial nature. The risk management database was developed using two approaches. The first approach uses a spatial module to integrate all disparate data and then designing an interface for adding new data as they become available ensuring that the risk calculations are up to date and relevant. The second approach uses an extensible architecture by its use of an API. Therefore, making it easy for state DOTs to add to its functionality as well as remove obsolete functions.

Finally, a risk management database provides a vital step to increasing the returns on investment of all the data collection investments both in new technologies and new initiatives and to translate the information to actionable intelligence for ensuring good stewardship of public funds.

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# CHAPTER 5. GENERAL CONCLUSION

Risk management analysis is one of the new requirements under MAP-21 and subsequently the FAST Act that separates transportation asset management programs (TAMP) from business as usual for the State departments of transportation (DOTs). Based on this requirement, each agency will discuss the concept of risk and how it should be incorporated into its transportation asset management program. This research used a state of the practice survey of all US state DOTs to identify how agencies were implementing the risk integration and what data were considered in that process. Based on that, the research proposed a data integration framework for implementing a risk management database of all relevant variables needed by an agency for its risk management activities. Finally, the research implemented the data integration framework using the Iowa Interstate 80 corridor from the Missouri River to the Mississippi River as case study.

The first paper presented findings from the state of the practice survey of how state highways agencies were integrating risk in their TAMPs as well as identified research needs to facilitate state DOTs compliance with the MAP-21 and FAST Act requirements. It included a discussion of agencies' TAMP readiness, the risk identification process, and what available data were used to generate the risk registers.

The second paper proposed a framework for designing and developing a risk management database by integrating all the relevant data that drives an agency's risk management process. It identified the challenges facing data integration implementation and recommended best practices for overcoming those challenges by proposing modifications to the risk identification process that is currently in place at all state highway agencies. The proposed modifications captures the qualitative and quantitative nature of risk management.

The third paper implemented the data integration framework using Iowa DOT data and risk registers to implement a risk management database. In the process, designed an API for data extraction, integration, and risk calculation. This chapter also provided guidance on how agencies can measure risk related to data collection and data modelling.

Typically, risk management is a collaborative endeavor among the various divisions that make up an organization. This research proposed a new way of doing risk register workshop that taps into the synergy demanded of effective risk management. The proposed approach to the risk register workshop provides for a risk-based investigation to focus data collection, identification of risk events and quantifiable measures, identification of critical assets to narrow focus, and adoption of similar data collection specifications to enhance seamless data sharing and less duplication of efforts. This will invariably improve the accuracy of the risk calculations and the utility of the risk management database.

## Limitations and Future Research

The scope of this research was to design and implement a data integration framework for implementing a risk management database, while this is an important contribution to risk management studies and integration in the DOTs TAMPs, it is just a first step. The goal of having all the relevant data integrated is to provide transportation officials pertinent and timely information in a systematic way in the face of risk events in order to make informed decisions and take action. To get to this point, there is need for risk modelling to produce risk profiles and baselines that will help agencies determines thresholds and triggers to guide the risk identification process as well as the risk mitigation process.

In order for any risk modeling to be successful, it has to be based on good quality data. As a result, there is need for a framework that helps agencies improve the quality and relevance of data already collected and how it integrates with future data collection to ensure consistency and model integrity.

State DOTs by nature are not monochromatic in the sense that they manage multiple assets across different divisions towards one objective. This warrants future research into the synthesis of a composite measure of risk and performance that reflects organizational needs. This composite measure should provide a systematic process for updating the risk assessment process in a way that identifies a linkage to decision making by providing a basis for comparing alternative improvement strategies (investment and policy approaches) and for tracking results over time.

From the review of the TAMP documents submitted by state DOTs, external events such as flooding and climate change ranked high in the risk register next to revenue variations which was number one. This prompts the need for better data collection during these events. In addition, the need for better correlation with expected outcomes versus actual outcomes. There is a great need to calibrate these external events especially as the frequency has increased and forecasted to continue to increase in the future.  It underscores the need for understanding the relationship between resiliency and risk considerations in effective risk management. There is need for research to document the extent to which implementation of measures across the risk management framework genuinely helps develop the attributes of a resilient transportation infrastructure.

Finally, the review of agencies’ risk registers revealed that all state DOTs have similar risks. This is not surprising since DOTs perform similar operations and functions, the only difference is geography. For instance, Iowa DOT will never have to deal with hurricanes while Texas DOT will never have to deal with the winter weather operations driving the deterioration of its pavement. The similarities of DOT functions and operations promotes the idea of creating a dictionary of risks and their possible mitigation taking into context their location and management focus. This augments well for a national risk register database to further drive the achievement of a national performance paradigm of the NHS. It is hoped that this research implementation of a database integration framework will also serve as a template that can lead to improved methodologies for integrating risk registers into the agency’s decision-making process and to foster a sustainable approach to dealing with uncertainties without undermining organizational efficiency.