Framework for Rating Roadway Assets at the Corridor Level

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Abstract

The United States relies on its vast network of roadways to transport people, goods, and services across the nation. These roads need to be maintained to an acceptable level in order to effectively provide a safe, reliable, and efficient road. The use of infrastructure management systems (IMS) has aided in keeping an inventory of existing roads, identifying assets in need of repair, and assisting in allocating funds for maintenance, repair, and rehabilitation.

The current practice in the United States has shown a lack of consistency in the way assets are rated in each state. Individual states have employed their own methodology for rating each asset type. This makes comparison of assets between states difficult. Several methods in use have provided a way to effectively rate an asset, but no method exists that can be used to compare ratings in different states.

To successfully maintain the network of roads across the United States, a method to assess assets between states is necessary. Consistency between states in their data collection, rating calculation, and rating reporting are all necessary to identify poor sections of roadway. Another useful reporting item will be a condition rating of all the assets contained within a corridor. A corridor is a series of travel routes which move people between two major points of interest.

By analyzing corridor level condition ratings, it will be possible to examine the overall condition of all the corridor sections across the nation and identify sections that need assistance in raising their condition.

The objective of this thesis was to develop a framework for rating assets at the corridor level. The framework was developed to be applied to any asset contained within a roadway and allow the combination of individual asset ratings into a single corridor rating. The final methodology

not only reports the overall corridor condition, but the functional and structural health of each individual asset, the rating of all of an asset type within a corridor, and performance indicators for individual items on a single asset.

The methodology was tested using data provided by the Virginia Department of Transportation (VDOT) to test if the methodology would produce ratings similar to those in use. For the application methods were developed for two major roadway assets; pavements and bridges.

The product of this thesis is a general framework which can be applied to roadway corridors to assess the overall condition of all the assets contained within the corridor's boundaries. It can be used in conjunction with an IMS to help improve and maintain the overall condition of the roads, which are critical to the United States. Without unification of condition rating methods into a single method it will never be possible to compare assets from every state in the nation.

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CHAPTER 1: **Introduction**

1.1. ***Background***

Infrastructure management systems (IMS) are tools that help engineers and planners make decisions about maintenance and rehabilitation techniques that extend or renew the life of critical assets. One set of assets that is essential to the United States is the National Highway System (NHS). The NHS is the major connection between every corner of the U.S. and is an economic lifeline that transports people, goods, and services. An effective asset condition rating framework, properly integrated into the IMS, can be a valuable highway decision making support tool to help optimize the operation of the NHS

Condition ratings are used to assign a numerical value to an asset's health based on visual or automatically-collected asset condition data. For highway networks, ratings can be used to describe the condition of individual elements, such as bridge elements, as well as the entire network. Engineers can use the ratings to decide which projects need the most attention, whereas policy-makers can use network condition ratings to appropriate funding to the different assets. Currently decisions are made at the asset level. The NHS consists of a combination of individual assets such as pavements, bridges, and safety features. These assets often have different sets of metrics used to determine their conditions and performance.

A highway's overall function is based on the performance of its various assets; including pavements and bridges. A condition rating of a highway should reflect assets as interconnected parts. A method of taking data that agencies across the U.S. collect and basing a condition rating system is the next step in bringing asset management to the corridor level.

1.2. ***Problem Statement***

Agencies across the country use condition ratings in the decision making process to allocate resources. Each agency has a methodology for rating individual assets such as bridges, pavements, safety features, etc. This has been documented in a synthesis which showed that each state has its own combination of condition ratings, goals, collection frequency and classifications (Papagiannakis et al 2009). In addition to having different methods for the same asset across states, different assets are also rated differently within a state.

As each agency uses its own method, the comparison of these numbers across the United States is difficult. NHS roads typically span two or more states and being able to evaluate the condition of a road along their length is critical to maintain the efficiency of the overall system.

The Federal government currently collects data from each state for pavements and bridges. Pavement data is typically presented as a single condition indicator, such as IRI, rutting, or cracking for the entire state network. Bridges are evaluated according to the National Bridge Inventory (NBI) Ratings. These ratings are often subjective and are generally not based on measured data, but do provide an indication of the state of the bridge (NCHRP 2009). To assist the government in identifying problem areas in the NHS based on both bridge and pavement assets, a condition rating and health index for the corridor level could be created to assign a single health value based on objective, measured condition data.

1.3. *Objective*

The objective of this thesis is to develop a methodology to assign a health rating to sections of road along a corridor. This rating would include the condition of pavements and bridges contained in a predetermined length of the corridor.

1.4. *Scope*

The researchers investigated the performance data currently being collected and the methods used to analyze pavements and bridges and rate their condition by different state DOTs and foreign agencies. The study examined which methods can be applied best to all states based on the types of data or practices the states employ. The thesis also proposed a method for rating the health of a highway corridor.

1.5. *Significance*

A method of calculating health indexes for corridors can provide information that can help identify those corridors, or sections within a corridor, that are in worst condition, compare them with the demand on those sections, and allocate funds for infrastructure planning, design, construction and maintenance more efficiently. Knowing which sections of roadway are most deteriorated could allow planning maintenance work on all the assets in a section at one time, potentially reducing the amount of cumulative closure time and increasing the quality of service provided to the users. Therefore, the proposed work can help FHWA and state DOTs by providing them with a uniform and objective approach for identifying problem sections within the NHS or a specific corridor.

The thesis provides agencies with a summary of the different methods and data currently used and collected by different state agencies and a methodology for calculating the health and condition of sections of corridor along a NHS route.

The study also provides an understanding of the lack of consistency in information among different methods for rating assets. The proposed method could potentially allow easier comparisons of the condition of corridors across the country.

1.6. *Thesis Overview*

The methodology developed in this research was based on the combination of several different asset condition rating methods used domestically and internationally. A study of each method was conducted to find practical methods that could be adapted for use on a national basis in the U.S.

Chapter 2 presents a literature review about current practice in asset management, condition assessments, and data collection. It contains methodologies which are being used by different states and different countries to assess the condition of their networks.

Chapter 3 presents a general framework for a proposed methodology for combining individual asset ratings into a single value for sections of corridors. The basic framework is provided to show the general idea that served as the foundation for the project.

Chapter 4 presents the details of the methodologies developed for this project. The methods reflect data that is currently collected but is developed using data provided by the Virginia Department of Transportation (VDOT). The equations and methods provided in this chapter can be further developed to be used at a national level but will need adjustment to be used by all the states.

Chapter 5 provides the results of applying the equations of chapter 4 to data provided by VDOT. The results of using the methodologies are presented as well as a comparison of calculated condition ratings to the condition ratings provided by VDOT. These are the CCI for pavement and the NBI for bridges.

Chapter 6 summarizes the project and provides recommendations for implementing the proposed method into current practice. It also includes a section that recommends future work that could be done to adjust the methodology and include more assets in the final rating.

CHAPTER 2: **Literature Review**

This chapter reviews the main sources of literature related to the National Highway System, current data collection practices, infrastructure management systems, and asset condition ratings. The chapter discusses the basic principles, collection methods, computer programs, and rating method equations.

Asset management in the United States has recently become a major priority for federal, state, and local agencies. Asset Management is defined as "a systematic process of maintaining, upgrading, and operating physical assets cost-effectively. It combines engineering principles with sound business practices and economic theory, and it provides tools to facilitate a more organized, logical approach to decision-making. Thus, asset management provides a framework for handling both short- and long-range planning" (FHWA 1999). Government agencies are increasingly adopting the asset management philosophy and attempting to establish asset management plans for the NHS. State agencies started implementing asset management programs with the goal of providing a way to maintain and preserve the estimated $1 trillion investment in Interstate highways and bridges that are contained in the NHS (FHWA 1999). This new focus on asset preservation has also fueled the development of asset management programs.

A critical subcategory of NHS routes is the Interstate Highway System (IHS). This system is the main lifeline for the movement of goods, services, and people since the 1950s. These routes are limited access highways that allow high speed travel from coast to coast. According to FHWA the right to freedom of choice and movement has been the basis of "the Nation's social, governmental, and legal principles" (Status of the Nation's Highways 2008).

As the system has aged, engineers have been faced with the task of maintaining, and more recently renewing, the system as both the demand and complexity and the public expectations for a well maintained roadway with a high level of service has steadily increased. At the same time budgets have, in general, not increased enough to reflect these higher demands and expectations. Asset management provides means for making proper use of the collected data to support asset maintenance and repair decisions. The three components of the asset management cycle that will be presented in this thesis are data collection, condition indexing, and individual asset management systems (computer-based systems).

2.1. ***Corridors***

Corridors can be defined as a collection of roadways, railways, marine passages, or air routes that allow easy passage of people and goods from one destination to another (NCHRP Report 632 2009). Corridors in the United States are generally based around the IHS and its routes that stretch across the country. For the purposes of this thesis, corridors are based on IHS routes that connect two major cities.

The economy of the United States is dependent on the condition of the IHS (NCHRP Report 632 2009). A high percentage of our traffic travels on these routes frequently. According to NCHRP (Report 632 2009) “Approximately 20 percent of all road travel by automobiles, trucks, and buses occurs on the one percent of miles represented by the IHS”. Not only is its condition critical to the U.S. economy, but also to the United States’ ability to compete in the international market. These roads allow goods to travel from central states to ports along the coast for international shipping and vice versa. Figure 1 shows the distribution of lane miles, vehicle miles travelled, and bridges by road classification.

To ensure the efficient flow of goods and vehicles, these corridors must be kept in good condition. . NCHRP (Report 632 2009) presents a list of items that are to be considered in the condition of the IHS. Only pavement and bridges are considered in this thesis

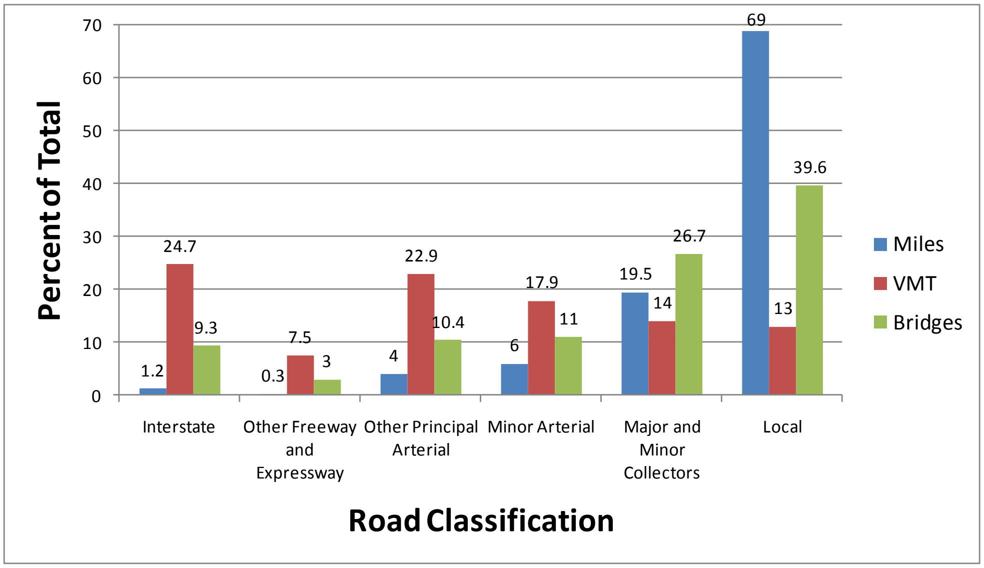

Figure 1: Distribution of Mileage, VMT and Bridges by Road Classification (FHWA 2008b)

2.1.1. **Public Benefits of Highway System Preservation and Maintenance**

Corridor condition is a major factor in the functionality of the IHS. A well-maintained system can have many benefits to both the governing agency and the public (Lemer 2004). Agencies have used life-cycle cost analysis (LCCA) to evaluate the benefits of different maintenance activities. LCCA has shown that using preventive maintenance (PM) at the right moment and more frequently can save agencies money as compared to major rehabilitation occurring less frequently (FHWA 2002). This is due to the relatively low cost of PM and the high cost of rehabilitation work. Also PM can help to extend the life of a pavement when applied at certain pavement condition levels.

To make sure that PM is applied at the appropriate time, agencies typically set trigger values on the pavement condition that indicate when a technique should be applied. As shown in Figure 2, the trigger level for PM is when the pavement is in better condition than for the rehabilitation trigger. The red line in the figure shows the original condition of the pavement and major rehabilitations made when the pavement reaches an unacceptable level. The blue line represents preventive maintenance activities performed at a high target level of condition. This target level represents an agency goal to keep the pavement at an acceptable performance level.

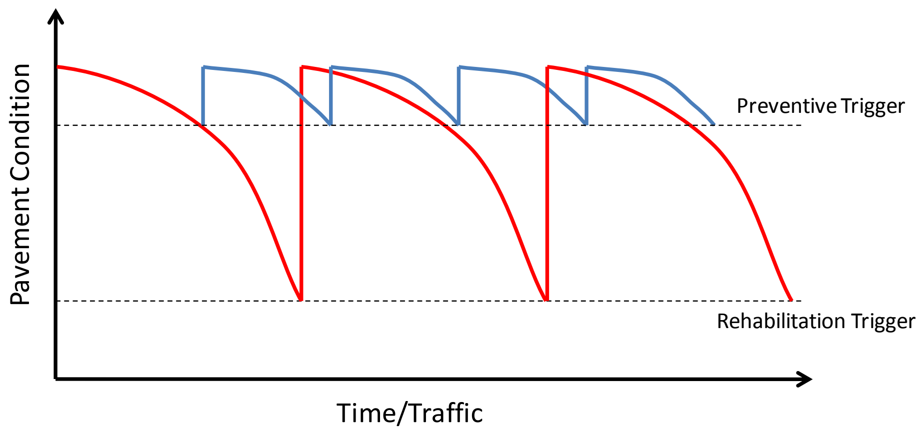

Figure 2: Preventative Maintenance and Rehabilitation Triggers (FHWA 2000)

The larger the required improvement in pavement condition, the more costly to the agency. Spending smaller amounts at the preventive trigger extends the life of the pavement and keeps it at a higher quality providing a better service to the users. If the pavement were not maintained, the condition would be as shown in the red line in Figure 2. If no actions are taken, the road has a shorter service life than if PM is performed. Shorter service lives lead to increased costs for the agency to maintain and rebuild the pavement section. Poor or non-existent maintenance schedules lead to the need for complete reconstruction of the pavement, which increases material and labor costs as well as user costs. These user costs can include traffic delay times, length of detour, congestion, fuel costs, etc. Minimizing these costs can improve public perception of the road network and the agency.

User costs are dependent on the network condition. The general public may not know the cause of cracking on a highway, but they will negatively associate these distresses with network performance. Public perception relies not only on the physical condition, but also on the functional properties of the roadway. Long delays and high traffic congestion lead to negative views of the roads. Increased delays and traffic can also lead to higher fuel costs and decrease the time a person spends at work or personal activities, impacting quality of life. Both of these not only affect the individual, but collectively hurt the economy. Figure 3 is an example of how condition affects both the user and agency costs.

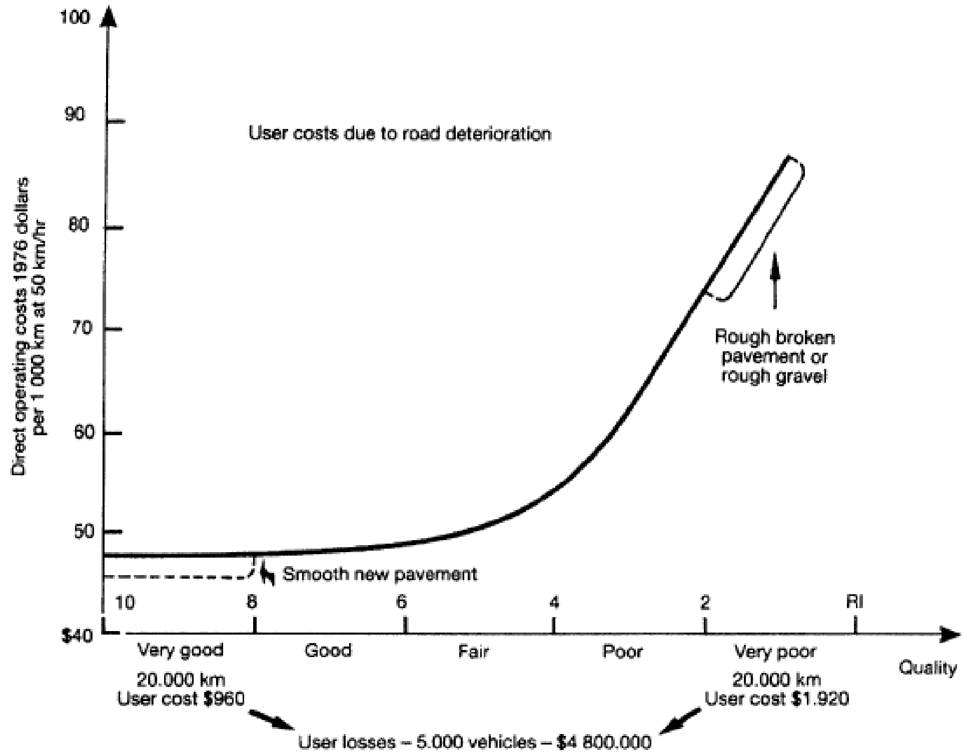

Figure 3: Relationship between User and Agency Cost to Pavement Condition (Lemer 2004)

The figure shows that as the Ride Index (RI) decreases the user and agency costs nearly double. Even though this is an old figure, the concept is still true. Poor condition networks will inevitably lead to higher costs. The only way to lower these costs is to keep the network at the best possible condition as long as possible. However, the range of condition for today's interstate highways is much narrower, and thus the difference between these costs is considerably smaller. However this may not hold for primary and secondary routes.

One way to decrease delays and improve public perception is to use PM techniques. Using these techniques can limit cumulative construction time and keep the road network condition at an optimum level as shown in Figure 2. Better condition roads can also lead to better traffic flow, as drivers will not need to avoid potholes, uneven bridge approach slabs, etc. Minimizing distresses, construction times, commuter travel time, maintenance costs, and non-serviceable lane-miles will be beneficial to users and owners alike.

To help determine what maintenance, repair, and rehabilitation (MR&R) actions will best benefit a corridor, there are several practices that need to be analyzed. These are the data collection process, the infrastructure management system, and the condition rating techniques. These practices are interconnected, but form the basis for MR&R techniques in the U.S. and around the globe.

2.2. *Data Collection Practices*

Currently most agencies collect basic data to show the condition of the roadways. Generally, this data is grouped into three evaluation categories: user, functional, and structural (Haas et al 1997). These categories can be used to describe data for all forms of infrastructure assets, but this thesis focuses on how bridges and pavements fit into these categories.

User evaluations focus on how the public views the infrastructure. It can relate to how comfortable their ride is and how satisfied they are with the asset. It is largely based on public opinion and usually has little to no supporting data to quantify these views. For pavements, engineers collect the Present Serviceability Rating (PSR) and traffic levels to assess how well the pavements are accommodating the public. For bridges, engineers rely on ride quality and traffic to assess the user perception of the bridge. This focuses mainly on the deck since this is the element the public encounters every time they pass over a bridge. This category

Functional evaluations are the engineers' method of understanding the user perception. These evaluations collect data that can be related to how well the asset is performing. Pavements condition has been described by the International Roughness Index (IRI), Present Serviceability Index (PSI), Pavement Condition Index (PCI) and Pavement Condition Rating (PCR). These values represent roughness, condition of the surface, and the advancement of deterioration. Soon this category will also include exact measurements of rutting/faulting and cracking as departments look to collect more of this data. Bridge functional evaluations are based on their sufficiency rating. This rating reflects several qualities about the bridge. These are the width of travel lanes, height clearances, deck surface quality, level of service, etc.

Most often user and functional evaluations are grouped into one category, as they are interrelated and impact each other. An example is how road roughness affects the user's perception of ride quality. Smooth roads will have low IRI values and the user will feel a smooth and comfortable ride. Also, high values of cracking could cause a user to see the road as being in poor condition, which it may very well be. This thesis considers user and functional evaluations as one category.

Structural evaluations are done to determine load-carrying capacity and remaining life of the asset. Structural evaluations of pavements are mainly done using Falling Weight Deflectometers (FWD) which is a device that drops a specified weight from a predetermined height onto the pavement surface in order to mimic an 18 kip wheel load. Geophones measure the deflection at certain distances from the center of the weight. If the thickness of the layers is known, the modulus of the various pavement layers can be determined. FWD tests are performed at select spot locations; but recently developed devices, such as the Rolling Weight Deflectometer (RWD) and the Traffic Speed Deflectometer (TSD), can collect continuous data at highway speed. Bridges are evaluated by load rating or executing a load test. This can be performed by using either a computer program to model the bridge in the current condition or by loading the structure with a vehicle and measuring structure deflections and strains. Either option can provide views into the capacity of the bridge and the safe operating load that can pass over the structure. If necessary, a seismic evaluation can be performed to ensure the bridge can withstand certain magnitudes of earthquakes.

In addition to the traditional user, functional, and structural categories mentioned above, safety has recently gained importance. Safety evaluations provide insight to the risks users are exposed to. Pavement safety can focus on items such as friction, rut depth, and even roughness. Friction relates to the ability of a vehicle to stop and maneuver. Ruts can cause the car to follow a certain track and not be able to maneuver away from the path quickly. Very rough roads can cause the vehicle to lose contact with the surface and cause damage to the vehicle. Bridge safety can be related to its deck quality, load rating, and friction on the bridge deck itself. These are similar to the pavement indicators, since a smoother ride with enough friction to stop and to maneuver is very important to vehicle dynamics. Clearances, vertical and lateral, are also safety considerations related to the original design of the bridge. Their influence can be affected by changes in future traffic types and volumes.

Highway agencies collect data that can fit into any one of these four categories. Each agency collects different quality measures, often using different equipment, which makes comparison between them difficult. However, Flintsch and Bryant (2006) have suggested that certain categories are more crucial to an agency's data collection needs. These are shown in Table 1, which suggests that most agencies rank the structural and functional condition of their assets as the most important pavement characteristics. As such structural and functional measures have become the most readily available measures of pavement condition.

Table 1: Survey Results of Factors Influencing Decision Making (Flintsch and Bryant 2006)

Roadway Asset Data	**Average Ranking**
Structural condition	*3.77*
Functional condition	*3.67*
Usage	*3.29*
Initial agency costs	*3.23*
Life Cycle Costs	2.96
Attributes/ characteristics	2.90
Customer/ user feedback and complaints	2.83
Location	2.67
Key: 4 = Very Important, 3 = Somewhat Important, 2 = Not Very Important, 1 = Not Important at All	

Finding similarities in data collection among agencies and asset types could lead to an improved method of condition rating along a corridor that passes through several jurisdictions. As shown in Table 1, agencies have similar views to what influences their project level decisions. The use of similar performance data collection methods can help agencies compare their pavements performance, as well as the performance of different construction and MR&R techniques. The following sections examine the current data that is being collected for pavements and bridges.

2.2.1. **Pavement Data Collection**

Data collection for pavement is used to evaluate current condition, determine maintenance, rehabilitation, and repair (MR&R) plans, and create deterioration models to predict future condition. The types of data collected depend greatly on the needs of the governing agency. For the Highway Performance Management System (HMPS), FHWA requires agencies to report data periodically. In addition, agencies typically also collect additional data to feed their pavement management systems (PMS).

A general outline of how agencies have established their PMS is presented in the AASHTO Pavement Management Guide (2001). This guide describes the general features of a PMS, such as data collection, data management, data reporting, predicting deterioration, needs analysis, and selection of candidate sections for MR&R.

One section of the guide describes the collection of condition assessment data for use in a PMS. It claims that "collecting pavement condition data is the most expensive element needed to keep the data current for PMS activities" (AASHTO 2001). It then explains that, for this reason, it is important to carefully select the type of data used in the PMS and check the accuracy and quality of this data. The general data items that AASHTO recommends for condition assessment are roughness, surface friction, structural capacity, rutting, cracking, shoving, bleeding, and faulting. Agencies are free to choose their own data for use in their PMS system, but the HPMS requires the reporting of specific data items on a frequent basis. The following sections discuss the HPMS reporting and the data items used for in-house decision making in a PMS.

2.2.1.1. Highway Performance Management System (HPMS)

The HPMS is a reporting system implemented by FHWA to keep records of different items along the national highway system (NHS), which include all interstate highway plus other routes important for national connectivity. Agencies are required to report traffic, inventory, roadway widths, parking, and pavement data. For the pavement data, agencies have been required to report data on the International roughness index (IRI) and present serviceability rating (PSR) for all sections of IHS and NHS on a biannual basis. IRI is reported as a mean between left and right wheel path as mean roughness index (MRI) in inches per mile (in/mi) or millimeters per meter (mm/m). The IRI is defined as the amount of longitudinal deviation from a true planar surface over a distance based on a Quarter Car simulation (Janoff et al 1975). PSR is reported on a 0 to 5 scale, which represents the observed deterioration of the pavement surface. A newly surfaced pavement would rate between 4 and 5, whereas a non-traversable route would receive a rating between 0 and 1.

HPMS Reassessment 2010+ (FHWA 2008) has recently been published to describe the changes that are to be made to the current set of data that is being reported. In this newest version, PSR requirements are to stay the same but measurements of IRI will slightly change. The goal is to have IRI measurements taken on a yearly basis. Although not all states currently perform these measurements regularly, the FHWA has required that states submit a plan as to how they will take the necessary steps to make the collection possible. This requirement was enacted in 2009 and states had to submit their plans by this year.

Some other changes occurring with the reassessment are the requirement of additional indicators, collection of IRI on certain structures such as bridges, year in which the IRI is collected, and an inventory of overlay thickness and dates of placement. HPMS now requires the reporting of cracking, rutting, and faulting of pavements. Rutting is to be recorded at the same time as IRI using the profilometer and is to be a sample data item. Cracking is to be recorded as a sample data item with the percent cracked. It will not take into account crack severity. The data are taken from a representative sample of the network. They are not currently collected continuously along the entire network length.

The data collected for the HPMS could easily be adapted to compute a health index for the pavement along a corridor. IRI, cracking, and rutting are three of the most important indicators in determining pavement health. With agencies required to submit the data every 1 to 2 years, the condition of the pavement can be updated yearly. This set of data matches the goal of the thesis by using data already collected on a consistent basis.

2.2.1.2. Pavement Management System Data Collection

In addition to data collected for HPMS 2010+, agencies can choose to collect their own data for in-house use. According to a NCHRP synthesis (Flintsch and McGhee 2009), surface distresses and ride quality are the most commonly measured pavement condition indicators at the network level. Figure 4 shows that most (98%) of American and Canadian agencies collect surface distress data at the network level. Of these surface distresses, over 75% of agencies already collect rutting, transverse cracking, fatigue cracking, longitudinal cracking, and map/block cracking. This shows that agencies had been collecting this data prior to the initiation of the new HPMS 2010+ requirements. In addition, 95% of the agencies collect smoothness data on a regular basis. Therefore, these will be the most feasible indicators to include in any pavement evaluation method.

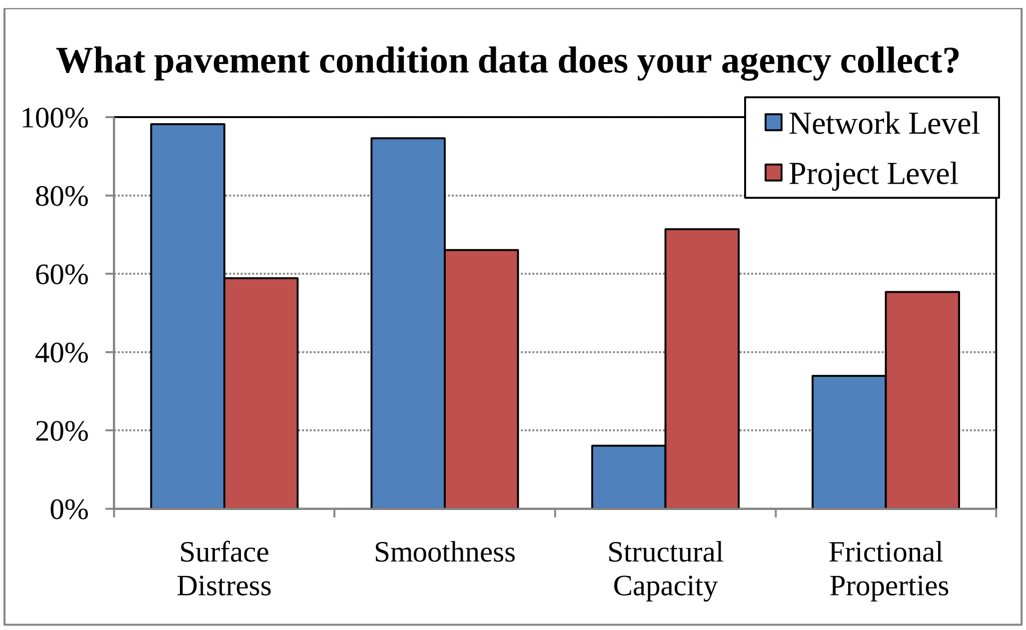

Figure 4: Types of Pavement Data Collected (Flintsch and McGhee 2009)

Furthermore, some states also collect structural capacity and surface friction. However, this is not done at the network level at a majority of agencies. Unless the HPMS requirements change to include these measurements, these data points will probably not be guaranteed to be collected at the network level at a high rate.

In a synthesis developed for FHWA by the Texas Transportation Institute (TTI), the different methods of pavement scoring were analyzed for every state (Papagiannakis et al 2009). Specifically the synthesis showed the high variability in the way states rate their pavements. Pavement condition indicators and scales for each pavement condition ratings varied from state to state. Sixteen states used a 100-point scale, thirteen used a 5-point scale, two used a 10-point scale, and ten states and the District of Columbia used other scales that are unique to their agency. This variability alone makes comparison between states difficult. These values are also calculated in different ways between states. Even within a state it was shown that the ratings could change. Oregon uses a 100-point scale for its NHS routes and a 5-point scale for its non-NHS routes (Papagiannakis et al 2009). The synthesis also showed how the rating scales are used to determine the proper maintenance treatment to be applied to the section. The types of treatments are similar but individual states use their rating scale to set different trigger values. All the differences between agencies add to the difficulty of comparing condition values between states across the U.S.

2.2.2. **Bridge Data Collection**

Bridge data is collected to determine the condition of individual components of the asset. These components are the superstructure, substructure, deck, approaches, retaining walls, etc. Each of these components contains several elements such as girders, bearings, joints, barrier walls, etc. Condition data can be calculated for either components or elements, depending on agency needs. Currently there are standards for reporting data regularly to the federal government. In addition, agencies collect their own data for use in their Bridge Management System (BMS). This data can be more detailed than what is reported to the government. The following sections examine the different types of data collection practices currently in use for bridges.

2.2.2.1. National Bridge Inventory (NBI) Ratings

The NBI is a federally mandated program that requires the inspection and inventory of bridge conditions on a two-year cycle. The program covers bridges and culverts that are twenty feet or more in length. The inventory is a collection of the inspection reports submitted by the inspectors. The reports include ratings on different bridge components such as superstructure, substructure, bridge deck and any channels that it passes over. The reports also include information on bridge location, lane widths, clearances above and below, load postings, and other general information about the bridge.

The inspection ratings can be subjective, as it is left to the inspector to assign a condition rating between 0 and 9 for each component. One problem with this system is the subjectivity of the evaluations; what may appear to be a 5 to one inspector may be a 4 by another's standards. The one point discrepancy can be the difference between satisfactory or deficient. In addition, unless notes are accompanied with the inspection, it is hard to tell which element(s) of the component are in the most need of rehabilitation. Another issue is that although 90% of the total component, such as the superstructure, substructure, etc., is in a good working condition the NBI rating will not reflect the 10% which could be in critical need of repair. An example could be a bridge with 5 spans, which has 4 excellent condition spans and 1 critically damaged span. If the entire superstructure is rated as one component, the rating will not adequately describe the problems with the deteriorated span. Although notes may be taken to supplement the ratings, only the numeric ratings are presented to decision makers. The one bad span could be more critical than a bridge with a lower overall rating, but the values will tell decision makers that the second bridge is more damaged.

The NBI does provide engineers with good evaluations of how the components of the deck are functioning, but it does not give an objective rating of the elements in the structure. It is a good system for reporting of condition to higher levels of government, which only need a general idea how a group of bridges are functioning, but it does not give a specific description of what the individual bridge needs.

Federal Bridge Sufficiency Rating

FHWA uses the NBI ratings to calculate a sufficiency rating (SR) for each bridge in the NBI system (FHWA 1995). It is used to evaluate bridges for qualification to receive federal bridge rehabilitation and replacement funds. The SR is based on a scale of 0 to 100, 0 being completely insufficient and 100 being completely sufficient. The scale reflects the bridges ability to carry traffic safely and have the proper structural and functional features to allow safe travel. The rating is based on Equation (1).

$$SR = S_1 + S_2 + S_3 - S_4 \quad (1)$$

Where,

S_1 = Structural Adequacy and Safety (55%)

S_2 = Serviceability and Functional Obsolescence (30%)

S_3 = Essentially For Public Use (15%)

S_4 = Special Reductions (6%)

Each of the S values is calculated by using NBI ratings of different components and guidelines set in the “FHWA Guide for Structural Inventory and Appraisal”. S_1 is based on the ratings of the deck, superstructure and the substructure as well as the load rating of the bridge. S_2 focuses on parameters such as average daily traffic (ADT), structure type, and several geometric parameters. S_3 accounts for detour length, ADT, and Strategic Highway Network (STRAHNET) highway designations. STRAHNET is the Strategic Highway Network, which is a network of roads which connect important military points of interest. S_4 are reductions that can be included if there are excessive detour lengths and insufficient traffic safety features. The percent values next to their descriptions are the maximum value for each. The values reflect the weight of certain NBI ratings to the overall condition of the bridge.

2.2.2.2. Element Level Inspections

An element level inspection involves a detailed report of each unit of measure for individual elements. Inspectors assign condition states to certain quantities of each element. Generally there are five condition states that an element can have. Each condition state reflects the condition between being like new, which is condition state 1, and in need of replacement, condition state 5. An example of an element level inspection report is shown in Table 2.

Table 2: Sample Element Level Inspection Report

CONDITION STATES					Element Description	Quantity Units
1	2	3	4	5		
0	350	0	0	0	Concrete Deck	$feet^2$
0	0	500	0	0	Steel Open Girder	feet
20	120	0	0	0	R/C Column	feet
1	0	1	0	0	R/C Abutment	each
35	6	0	0	0	R/C Cap	feet
0	40	15	0	0	Joint Seal	feet
0	18	0	0	0	Moveable Bearing	each
0	18	0	0	0	Fixed Bearing	each
2	0	0	0	0	R/C Approach Slab	each

2.3. *Infrastructure Management Systems*

Different engineering management systems are used for managing individual assets, including bridges, pavement, safety features, pipelines, etc. Advances in computing technology have allowed these systems to store and analyze large amounts of data regarding these assets. The systems can help manage an inventory of assets, model the past and predicted deterioration of an asset, and be used as a decision-support tool for analyzing needs, prioritizing projects, and developing work programs. These systems have similar features, but have different features that are unique for the type of asset being managed. The following sections discuss the management systems for pavements and bridges.

2.3.1. **Pavement Management Systems**

Aside from what is reported to the federal government, state agencies use their pavement management system (PMS) to keep records of all pavement sections. The specific functionality of the systems differs but they all share the same basic purpose and framework (AASHTO 2003). Each PMS is constructed of data collected by the agency and stored for analysis. The type of data collected varies from agency to agency. However, almost all the agencies keep record of pavement cracking and smoothness, which are values that will be required with HPMS 2010+. The PMS can help determine deterioration rates of similar pavement sections and assist engineers in properly allocating funds to different projects. Some of the main systems providers include DEIGHTON, Agileassets, and Stantec.

The first PMS systems were created in the 1960's and were primarily used at the project level (Hudson and Hudson 1994). These early systems focused on improving designs, maintenance, rehabilitation, and performance modeling. In the 1970's the use of PMS became primarily a network level tool that "involved the programming, planning, and budgeting of funds for entire networks of varying sizes" (Hudson and Hudson 1994). Since the 1970's PMS has primarily been used at the network level and still has the same basic functions.

The basic functions of most PMS are maintaining inventory, keeping records of condition data, modeling and predicting deterioration patterns for pavement sections, performing budgeting operations, and assisting in identifying sections that are good candidates for MR&R actions. These functions assist engineers organize projects within a network and make recommendations as to which projects should be executed first.

2.3.2. **Bridge Management Systems**

BMS are systems in which agencies can create their own databases of bridges. These databases can include everything from element level inspection data, NBI data, clearances, lane widths, or any other data the agency uses in its decision making process. These systems are chosen by individual agencies depending on their needs. While a few agencies have created their system in-house, most use commercially or publically available systems. The most popular system is Pontis, which is available as an AASHTOWare product for agencies to use and adapt to their own uses. Bridgit is another software package that was made available to all DOTs, but is not as widely used as Pontis.

2.3.2.1. Pontis

"Pontis supports the complete bridge management cycle, including bridge inspection and inventory data collection and analysis, recommending an optimal preservation policy, predicting needs and performance measures for bridges, and developing projects to include in an agency's capital plan” (Robert et al 2003). This sentence best summarizes what Pontis is and what its capabilities are.

Pontis was first developed in 1989 for the Federal Highway Administration (FHWA). It was originally released with, and is currently a component of, the AASHTO BRIDGEWare suite. This suite is a collection of software to use in the design, load rating, and management of bridges. Pontis is paired with Virtis and Opis. Virtis is a load rating database for bridges and Opis is a bridge design software package (AASHTO 2007). The trio of software packages can be a very valuable tool to major departments of transportation.

Pontis was designed as software that could be licensed out to different states to have a general program for them to use. As of 2005 there were 39 state agencies, 7 other U.S. agencies, and a few international agencies using Pontis. Some of these international agencies include Hungary, Estonia, Portugal, Italy, and Hokkaido, Japan. As of 2007, there were 45 state agencies that use Pontis (Hammad 2007).

Pontis can be run to do several functions that support the entire bridge management life cycle. The four major areas are inventory, inspection, needs assessment and strategy development, and project and program development (AASHTO 2003). According to the Pontis manual, most agencies use either the inventory and inspection or the needs assessment and project development sections (AASHTO 2003). Sometimes an agency will use all four, but it depends on the needs of the individual agency.

Pontis databases generally contain all NBI data and sometimes a list of element level inspection items. The database contains component-based ratings and more detailed information on the elements that make up the component. In addition to the inventory, the software has the ability to model the deterioration of elements based on past performance and deterioration rates. This information can then be used to create maintenance schedules for certain bridge elements.

AASHTO has created a list of Commonly Recognized (CoRe) Elements that are for use in Pontis and any other BMS. The list contains many elements that are common on most bridges. However, this list can be modified by each agency to fit their system. This versatility has made Pontis the standard in BMS.

2.3.2.2. Bridgit

Bridgit is not as flexible as Pontis, since it is used mainly for determining MR&R actions (Hammad et al 2007). The Bridgit software package can be used to keep historical records, schedule, estimate the cost, and create a list of MR&R activities. Bridgit software consists of five different modules - the Inventory, Inspection, MR&R, Analysis, and Models modules (Hawk 2000). Although these five options are available, users of Bridgit mainly use the MR&R module due to the ability of this module to monitor several different MR&R aspects (Hammad et al 2007). These include MR&R planning, scheduling, recording, and monitoring of action results.

2.3.3. Similarities and Differences in PMS and BMS

PMS were the first infrastructure management system to be developed and used by the engineering community. It was in use for two decades until bridge engineers recognized that the concepts used in PMS could be applied to bridges (Hudson and Hudson 1994). The realizations lead to the development and use of BMS to maintain bridges in the United States and around the world. Bridge management is now a common practice. From these systems, other forms of infrastructure management have been used for assets such as buildings and sewage systems. PMS and BMS are still the most widely used systems for asset management.

The data collected for use within the PMS and BMS can be the foundation for the creation of a health index system for corridors. Each system can store inventory data, condition ratings, technical parameters, and background information on an asset. Most systems are also in an agency's computer network, which allows them to be easily shared between offices. Another quality of both systems is their adaptability. Every agency can change the program to meet their individual needs in decision making and maintenance.

The major difference in the two systems is the type of asset that it manages. The data needed to represent pavements can be very different from that of bridges. The technical parameters that measure pavement distress have actual values associated with them, where as the current practice for bridges just requires a single subjective rating. However use of element level inspection data can allow an agency to attach a quantitative value to an element, allowing an objective approach to condition rating of bridges.

Although these systems are slightly different they are generally similar in their function and capabilities. They allow engineers to store the data, calculate current condition and develop accurate deterioration models based on past performance.

2.4. *Infrastructure Condition Rating Techniques*

Currently, several techniques for both pavements and bridges are available to analyze the condition of the asset. The result of the analysis is a numerical value that represents the condition or "health" of a particular asset or set of assets. The following sections will examine the different type of condition rating techniques that are used for bridges and pavements, both domestic and internationally.

2.4.1. **Pavement Ratings Used in the United States and Internationally**

Pavement ratings used in the United States vary greatly from state to state. States use rating methods that incorporate the data collected for in-house use. Some states use the same method, but it is very difficult to compare ratings between states due to the variability in the inputs for the ratings, the scale of the ratings, and what the state agency considers acceptable. As shown by Papagiannakis (2009) there is great variability in the pavement rating scales alone. Currently there are sixteen states using a 100-point scale, thirteen using a 5-point, and two using a 10-

point. In addition there are ten states and the District of Columbia which use a custom scale to fit their pavement rating. There is also variability within a state. Oregon uses two scales: 100-point for NHS and 5-point for non-NHS. This further complicates the ability to compare pavement ratings between agencies. As shown in Table 3, there are several methods being used across the United States. One pavement rating method used outside the United States is the COST Method. This method was developed through a collaborative effort between several countries of the European Union, with participation from the United States. The project's main objective was to allow comparison of ratings between nations and to better understand the condition of the roads in the EU.

Table 3: Summary of Pavement Evaluation Techniques (Papagiannakis 2009)

State	Rating Method	Input Data	Scale	Scale Ranges
Arizona	Present Serviceability Rating (PSR)	Visual Inspection	0 to 5	N/A
California	Pavement Condition Survey (PCS)	Visual Inspection	1 to 5	1 and 2 are Excellent and Good
Colorado	Remaining Service Life (RSL)	Visual Inspection (Only major highways)	0 to Inf.	RSL>11 is Good, RSL between 6 and 10 is Fair
District of Columbia	Pavement Condition Index (PSI) - ASTM D6433-99	Visual Inspection	0 to 100	N/A
Florida	Pavement Condition Rating (PCR)	Inertial Profiler and Visual Inspection	0 to 10	10 is best, 6 not deficient is speed limit less than 50mph, 0 is worst
Illinois	Pavement Condition Survey (CRS)	Visual Inspection of images by raters	0 to 9	7.6 - 9 Excellent, 6.1 - 7.5 Good, 4.6 - 6.0 Fair, <4.5 Poor
Kansas	Performance Level (PL)	Visual Inspection	1 to 3	1 - Smooth/No Distress, 2 - Require routine maint., 3 - require rehab
Louisana	Condition Index and IRI	ARAN system	IRI Values	Acceptable Levels set for Different Classes of Roadway
Maine	Pavement Condition Rating (PCR)	ARAN system	0 to 5	N/A
Maryland	No Index - Use rutting and cracking data	Visual Inspection	N/A	N/A
Minnesota	Ride Quality Index (RQI), Surface Rating (SR), Pavement Quality Index (PQI - Combination of RQI and SR)	Visual Inspection	RQI: 0 to 5, SR: 0 to 4, PQI: 0 to 4.5	N/A
Michigan	RQI, SR, Distress Index (DI), RSL	Images and profiles from vehicle technology, cracking contracted	SR: 1 to 5	4 - 5 Poor, 3 - 3.5 Fair, 1 - 2.5 Good
Nebraska	Nebraska Serviceability Index (NSI)	Digital Photos and Visual Ratings	0 to 100	Ratings directly related to IRI. IRI < 0.82 m/km - Very Good, IRI > 4.21 - Very Poor
New Mexico	New Mexico-designed PSI (=60% IRI + 40% surface distresses)	Visual Inspection rated by local University	0 to 5	Good Condition: Interstate PSI > 3, Other PSI > 2.5
North Dakota	Public Ride Perception Index (PRPI)	Distress through Pathway van the worst 15% IRI.	0 to 3	0 - 1.3 Excellent, 1.3 - 2.0 Good, 2.0 - 2.8 Fair, > 2.8 Poor
Pennsylvania	Overall Pavement Index (OPI)	Video Logging, images then visually rated	0 to 100	0 - Worst, 100 - Best
Utah	Flexible: Environment Cracking Index (ECI), uses cracking info	Visual Inspection	N/A	N/A
Vermont	Currently PCI, will use Structural Distress Index (SDI) developed by Deighton	ARAN system	0 to 100	100 to 40 Acceptable, < 40 Unacceptable
Virginia	Critical Condition Index (CCI)	Automated through digital images	0 to 100	> 90 Excellent, 70 - 89 Good, 60 - 69 Fair, 50 - 59 Poor, < 49 Very Poor
Washington	Pavement Structural Condition (PSC)	Visual Inspection	0 to 100	100 Excellent, 100 - 50 Good, 50 Fair, < 50 Poor
Wisconsin	Pavement Distress Index (PDI)	Visual Inspection	0 to 100	0 - 19 Very Good, 20 - 39 Good, 40 - 59 Fair, 60 - 79 Poor, > 80 Very Poor

2.4.1.1. ASTM D6433-03

The Pavement Condition Index (PCI), developed by the U.S. Army Corps of Engineers, has been documented by ASTM as a standard method for measuring the condition of pavement surfaces. The PCI was developed for the PAVER management system (PAVER 1997) and has been adopted by several local agencies. Furthermore, several states have adopted modified versions of this index (e.g., Virginia, Hawaii, Iowa, and New York)

The PCI is measured on a scale from 0 to 100. To calculate the PCI of a section, the engineer starts with a value of 100 and proceeds to deduct values based on type and severity of distress. In a typical report for a pavement section, each distress and its quantity for each occurrence are reported. If a section has two types of the same severity, a row in the report is dedicated to each severity. Each column for the severity indicates the amount of the distress at each location it is found. An example is shown in Table 4.

Table 4: Sample Flexible Pavement Condition Survey for PCI Method (ASTM 2003)

Section Area = 2500 sq. ft.

Distress/Severity	Quantity							Total	Density (%)	Deduct Value (DV)
Alligator Cracking / Low	5	4	4					13	0.5	7.9
Alligator Cracking / High	8	6						14	0.6	23.4
Edge Cracking / Low	32	15	18	24	41			130	5.2	7.5
Joint Reflection Cracking / Medium	20	15	35	27	23	10	13	143	5.7	25.1
Patching / High	12	10						22	0.9	17.9
Potholes / Low	1							1	0.0	11.2
Rutting / Low	4	9	8					21	0.8	6.9
Weathering & Ravelling / Low	250							250	10.0	5.3

As shown in Table 4 each severity is recorded as either a count of a distress type or measure of the affected area by distress for a selected area of the pavement surface. The total quantity of each distress is recorded. This value is divided by the total extent of the distress type to determine the density of the distress. These distress densities are used with the distress type and severity to calculate the deduct values. Figure 5 is an example of the graph used to determine the deduct value for joint reflection cracking. The lines drawn show where the deduct value of 25.1 is on the figure.

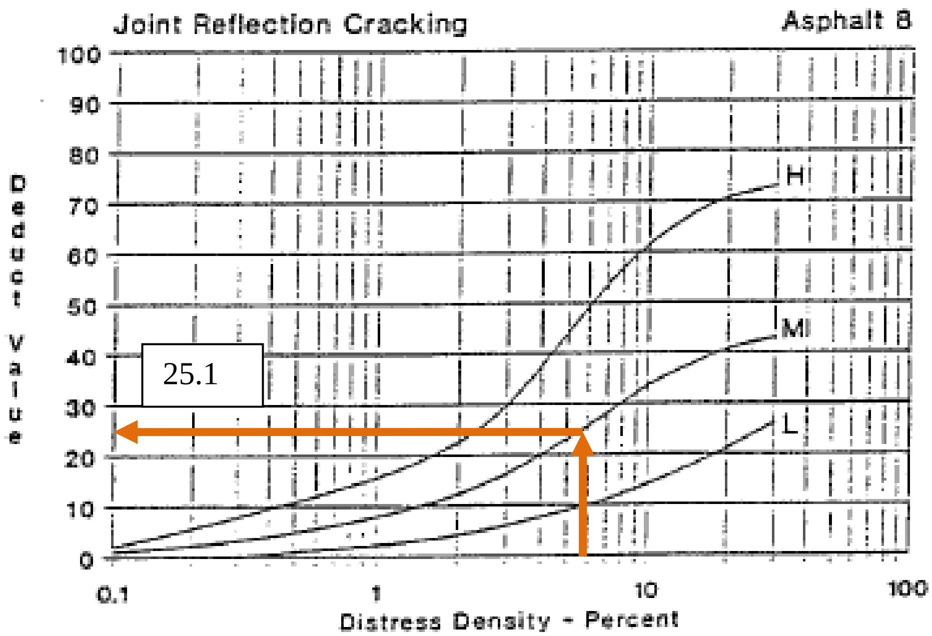

Figure 5: Deduct Values for Joint Reflection Cracking (ASTM 2003)

The PCI Method has a graph to determine deduct values for each distress. The next step is to determine the maximum number of deducts. This is used to limit how many deducts can be included based on each distresses contribution to the total deduction. This is done by taking the maximum deduct value (HDV) from Table 2 and inserting it into Equation (2).

$$m = 1 + \left(\frac{9}{98}\right)\left(100\text{-HDV}\right) \leq 10 \qquad (2)$$

Where,

m = Maximum Number of deducts

HDV = Highest Deduct Value

For the example in Table 4, the HDV is equal to 25.1. When this is used in Equation 2 the value of m is 7.9. Therefore to calculate the maximum corrected deduct value (CDV) the seven highest deduct values and 0.9 times the eighth highest deduct are summed. All of these deducts are totaled and are correlated on a graph with the number of deducts, q, which will produce the CDV value. This graph is shown in Figure 6. To use this graph calculate the sum of all the deduct values (TDV), take your number of deducts (q), and follow the curve to the y-axis to get the CDV for this section.

The next step is to perform iterations to ensure that including all deductions produces the highest CDV. As shown in Table 5, deduct values are arranged from highest to lowest value. The first iteration includes all calculated deductions in the calculation of CDV. Each iteration then takes the lowest deduct and changes the value to 2. All deducts in this iteration are added and Figure 6 is again used to calculate a new CDV. These iterations are done until only the largest deduct value remains in its original value. Table 5 shows each of the iterations and its associated CDV value.

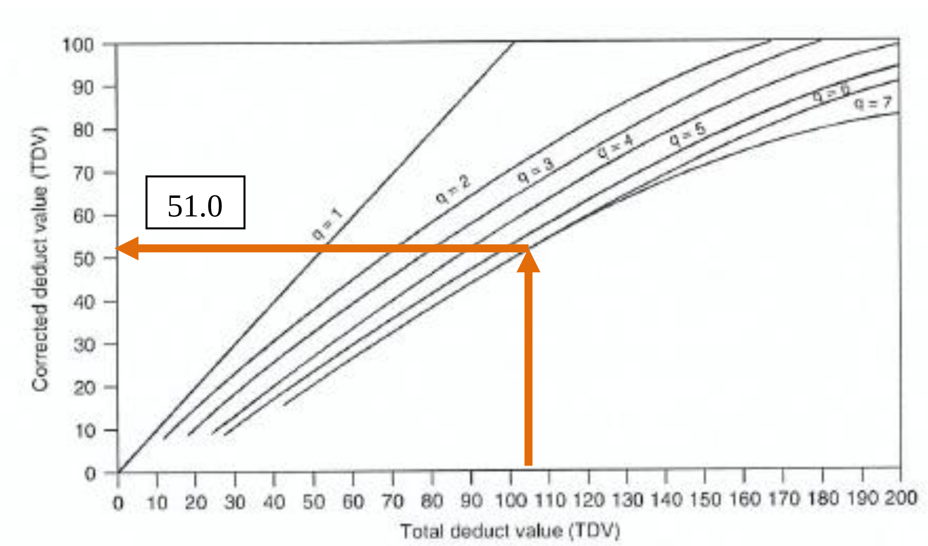

Figure 6: Graph relating Total DV to CDV (Papagiannakis 2009)

Table 5: Sample Calculation of Max CDV (ASTM 2003)

Iteration	Deduct Values								Total	q	CDV
1	25.1	23.4	17.9	11.2	7.9	7.5	6.9	4.8	104.7	8	51
2	25.1	23.4	17.9	11.2	7.9	7.5	6.9	2	101.9	7	50
3	25.1	23.4	17.9	11.2	7.9	7.5	2	2	97	6	46
4	25.1	23.4	17.9	11.2	7.9	2	2	2	91.5	5	47
5	25.1	23.4	17.9	11.2	2	2	2	2	85.6	4	48
6	25.1	23.4	17.9	2	2	2	2	2	76.4	3	48
7	25.1	23.4	2	2	2	2	2	2	60.5	2	44
8	25.1	2	2	2	2	2	2	2	39.1	1	38

This value of CDV will then be used in the final calculation of the PCI for this section. This is shown in Equation (3).

$$PCI = 100 - \max CDV \qquad (3)$$

Where,

PCI = Pavement Condition Index

max CDV = highest value of CDV calculated

For this example the PCI is 49. This relates to a "Fair" condition for this section. ASTM sets a range of values for each condition rating label. The ranges classify the pavement sections into different classifications. These ranges are as follows:

85 - 100 Excellent

70 - 85 Very Good

55 - 70 Good

40 - 55 Fair

25 - 40 Poor

10 - 25 Very Poor

0 - 10 Failed

This method has become the ASTM Standard, although it is not greatly used at the state level. It does provide a method which incorporates many types of distresses and their different severities.

Some states have adjusted this methodology to fit their agency's preferences. Typically they have reduced the number of distresses considered when adapting this method.

2.4.1.2. Virginia DOT Critical Condition Index (CCI)

Virginia DOT (VDOT) has adapted a modified version of the ASTM D6433 method to use on its network of roads. VDOT believed that a distinction needed to be made between distresses that were caused by loading in the wheel path and those that are the result of environmental or non-load related distresses (McGhee 2002). A summary of Load Related and Non-load Related distresses is shown in Table 6.

Table 6: Different Load and Non-Load Related Pavement Distresses (McGhee 2002)

Load Related Distress	**Non-Load Related Distresses**
• Alligator Cracking • Delaminations • Patching • Potholes • Rutting	• Bleeding • Block Cracking • Linear Cracking • Reflection Cracking

These two categories of distress are then used separately in a rating system based on the PCI. It is also based on a scale of 100 and uses custom deduct values adjusted for use by VDOT. Each category of distress has a separate condition index. The Load Related Distress Index (LDR) uses those distresses in the first column of Table 6. The Non-Load Related Distress Index (NDR) uses the distresses in the second column. These indexes provide useful information in the agency's PMS decision trees.

The minimum of LDR and NDR determines the Critical Condition Index (CCI) which is used to classify the overall condition of the segment. This method is based on the understanding that using PCI to calculate the deduct values for all distresses in one index can lessen the effects of load and non-load related distresses. Therefore, the method was adjusted to fit the needs of VDOT in their planning for maintenance actions for the pavement in the state.

2.4.1.3. Washington State DOT Pavement Rating System

Washington State DOT (WSDOT) originally used a method called Present Condition Rating (PCR). The method was similar to the PCI in that it uses deduct values for each type of distress. It did not use a corrected value for deductions but utilized a roughness measure, CPM. CPM was a measure from a roughness measuring device used by WSDOT. The PCR is calculated according to Equation (4)

$$PCR = (100 - \sum D)(1.0\text{-}0.3\left(\frac{CPM}{5000}\right)^2) \quad (4)$$

Where,

PCR = Present Condition Rating

D = Deduct value for each distress

CPM = Roughness measure

One major problem with PCR was that negative values can be obtained if a section had numerous distresses. There was no limitation on the number of deductions. Therefore, in 1993 WSDOT switched to a new method called the Pavement Structural Condition (PSC). The PSC is obtained from the equivalent cracking (EC), which combines the distresses into a single measure. The PSC is calculated according to Equations (5) and (6) for flexible and rigid pavements, respectively.

$$PSC = 100 - 15.8EC^{0.5} \text{ (Flexible)} \quad (5)$$

$$PSC = 100 - 18.6EC^{0.5} \text{ (Rigid)} \quad (6)$$

Where,

PSC = Pavement Structural Condition

EC = Equivalent Cracking

The method for calculating EC was different for flexible and rigid pavements. WSDOT uses the PSC to determine when a section of pavement needs rehabilitation. PSC values lower than 50 triggers the action (Papagiannakis 2009).

As of 2009, WSDOT was in the process of revisiting their rigid pavement condition indices. Proposed are three individual pavement condition indices; Rigid Pavement Cracking Index (RPCI), Rigid Pavement Faulting Index (RPFI), and Rigid Pavement Wear Index (RPWI). Each will use deduct values specific to each index. These deduct values are calculated by setting the maximum limit of the distress with 100 deduct value and drawing a log-log plot as shown in Figure 7. The proposed rigid pavement condition index is calculated by taking the average of the three indices and subtracting one Standard Deviation (Papagiannakis 2009).

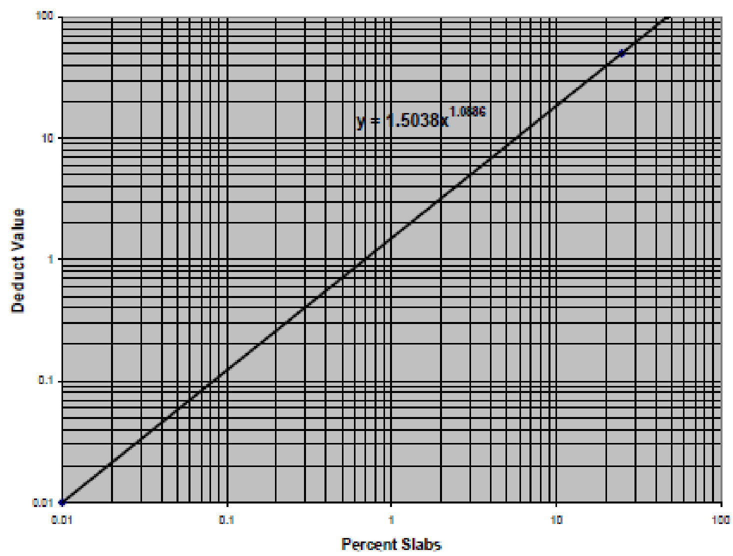

Figure 7: Deduct Values for Single Transverse Cracked Slab (Papagiannakis 2009)

WSDOT has reexamined its methodology to make it applicable to all of their pavement sections. It does mean that these values are easy to compare with other states. The same can be said about the VDOT CCI. Even though the WSDOT and VDOT methods have the same scale, the scale represents a combination of differently weighted distress deduct values. If these methods were to produce the same rating, they would need to include the same distresses and weights. Until this is done it will be nearly impossible to accurately compare pavements on a national level, regardless of the state.

2.4.1.4. COST Method for Evaluating Pavements

In 2008 the European Cooperation in the field of Scientific and Technical Research (COST) released their final report of action 354. The action's main objective was to define "uniform European performance indicators for road pavements taking the needs of road users and road operators into account" (COST 2008). This was to be done by using "quantitative assessment of different aspects of pavement performance."

The final product of this action was a method of using measured single technical parameters and transfer functions to develop single performance indicators (PI). The PI values can be used to calculate combined performance indicators and general performance indicators. This method of calculating indicators was designed to be used across the 23 European countries that took part in the COST conference.

To develop this system, a survey was conducted to determine what technical parameters were already being collected. From this list, a set of performance indicators were established. These include longitudinal evenness, transverse evenness, macro-texture, friction, bearing capacity, cracking, noise, and air pollution. Small groups were formed from these indicators to create a combined performance indicator in a certain area such as safety, comfort, structural, and environmental.

The first step of the action was to collect a list of common technical parameters that were collected across Europe. Some examples of technical parameters are IRI, rut depth, mean profile depth, cross-fall, sand patch value, grip number, friction, structural number, deflection, etc. The goal was to find a list of technical parameters that were the most commonly collected to allow similar analyses from country to country.

These were then grouped into different categories of performance indicators (PI) that represent different pavement characteristics. These include longitudinal evenness, transverse evenness, macro-texture, friction, bearing capacity, cracking, noise, and air pollution. From the set of technical parameters a preferred quality measure was selected to create a transfer function that will take the technical parameter and convert it to a PI. PIs are on a scale of 0 to 5, 0 being the best. Equation (7) is an example transfer function for longitudinal evenness, PI_E:

$$PI\_E=Max(0;Min(5;0.1733*IRI^2+0.7142*IRI-0.0316)) \quad (7)$$

The IRI units in Equation (7) are mm/m. For example a PI_E of 2 corresponds to an IRI of 1.9 mm/m (120.4 in/mi) and a PI_E of 5 is an IRI of 3.7 mm/m (234.4 in/mi).

A transfer function was created for each of the different PIs considered. For cracking and surface defects the area, length, and element cracking are combined in a single technical parameter. The combination takes into account the severity, weight, and type of crack or defect. The weight of each type is given in tables within the report. They provide a typical range and a mean and median weight values. The weights are scaled so that the maximum weight is equal to 1 by multiplying all the weights by:

$$x=\frac{1}{max\ (W_1;W_2;\ldots;W_n)} \quad (8)$$

If the highest weight is less than one the x value will be greater than one. This will raise the W_n to one and scales the other weights appropriately. All of the different defect types are then summed and the area affected by the distress is divided by total area in order to get a percent area which has defects. The three technical parameters of area, length, and element are then added to get a total percent area affected of cracking or defects. This technical parameter can then be used to calculate a PI in a similar to the method used for evenness (Equation 7).

The individual PIs that can then be used to calculate different combined performance indices (CPIs). These CPIs represent structural, comfort, safety, and environmental indicators. The report includes a table with minimum, standard, and optimum groupings of PIs that would be used to calculate the CPIs. For the Comfort CPI the standard list includes PI_E, PI_SD, and PI_R, which correspond to evenness, all surface defects, and rutting, respectively. This list is a way to make sure all the indicators that affect a rider’s comfort are included.

To calculate the CPI, a weighted value for each PI is used. For a given PI, these depend on the CPI category considered and reflect the importance and relevance of the PI to the CPI category. The report presents two alternatives for calculating CPI. One equation uses all the (weighted) PIs included in the category and the other uses just the two highest values of PI. The report recommends the first equation for CPI. The equation is:

$$CPI_i = \min[5; I_1 + \frac{p}{100} * avg(I_2, I_3, \ldots, I_n)] \quad (9)$$

Where,

$I_1 \geq I_2 \geq I_3 \geq \cdots \geq I_n$

$I_1 = W_1 * PI_1; I_2 = W_2 * PI_2; \ldots; I_n = W_n * PI_n$

p = 20

A higher p value represents more influence of the other PI values. The p value can range between 10 and 20, but a base value of 20 was used throughout the COST demonstration.

The CPI can give an owner/operator an objective value of safety, comfort, or structure of the road based on collected technical data. This can direct the attention of maintenance crews to certain areas of concern within a particular segment of road.

The CPI can be related to the concept of Remaining Service Life (RSL). The way the PI values are combined takes the rating of the worst distress and decreases the CPI based on other distress conditions. If all distresses have low ratings (i.e. less distress) then the overall rating of the section is low. This equates to a longer RSL. As the CPI rating increases with the addition of distresses, the RSL decreases.

The report also provides a similar method of calculating a general performance indicator (GPI). GPI values are calculated in a similar way to CPI values. GPIs take all the CPI values and combine them into one value that represents the overall condition of the pavement. These values can be used to give, as the name implies, a general condition of the pavement regardless of evaluation category. The numbers can be reported to government officials who only need the overall condition of the pavement. To calculate the GPI a similar equation to the CPI was used. This is shown in equation 10:

$$GPI_i = \min\,[5; I_1 + \frac{p}{100} * avg(I_2, I_3, \dots, I_n)] \tag{10}$$

Where,

$I_1 \geq I_2 \geq I_3 \geq \cdots \geq I_n$

$I_1 = W_1 * CPI_1; I_2 = W_2 * CPI_2; \dots; I_n = W_n * CPI_n$

p = 20

The equation uses the same p value to determine the influence of the best CPI values. The weights are also similar in how they were determined. The weights and p value were determined through the use of surveys to all the European agencies. The weights for the GPI values were presented in graphs and are based on the type of road, type of CPI, and the person who completed the survey. A graphical representation of the overall process is shown below:

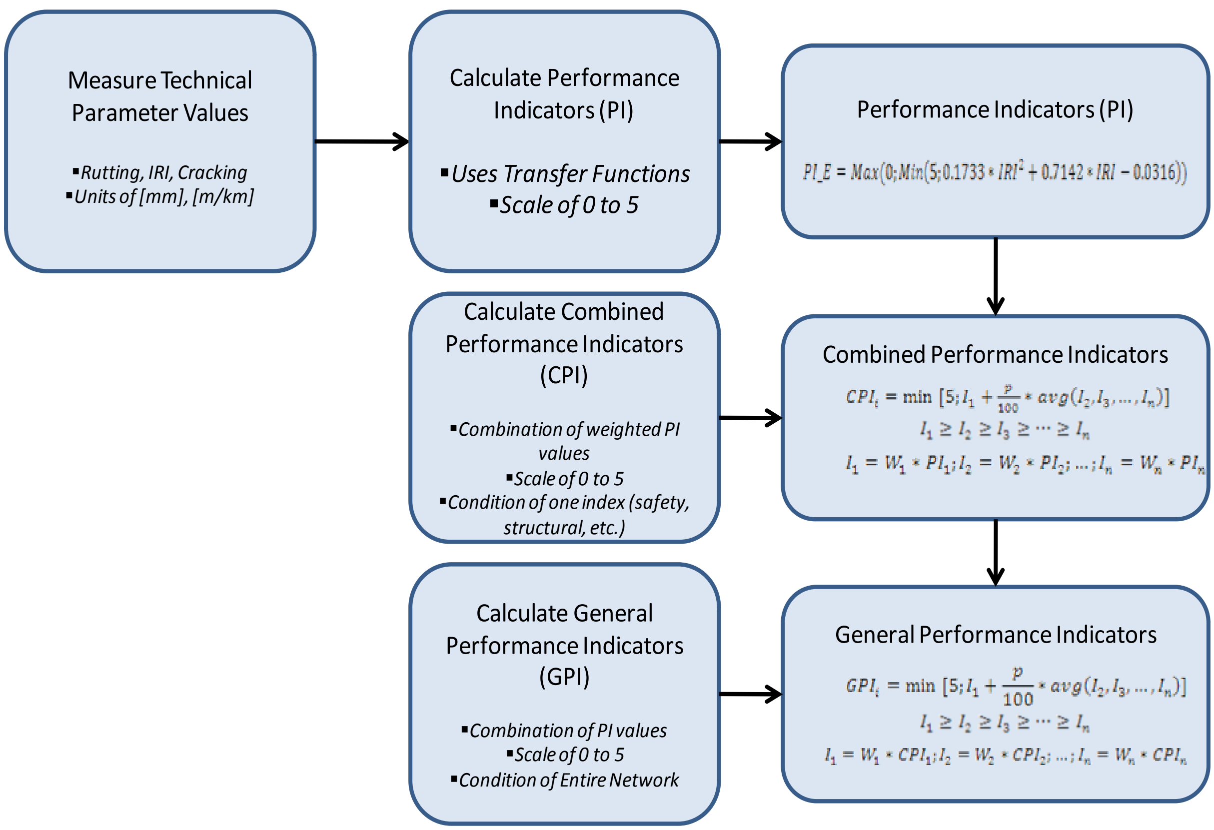

Figure 8: Overall COST Method Procedure

The COST Method has shown to be an effective network rating system that demonstrates the efforts towards international cooperation (COST 2008). It provides an objective rating based on collected data which is common throughout the EU.

2.4.2. **Bridge Rating Methods Used In the United States and Internationally**

There are several methods currently available to evaluate bridge health. The United States main system is the NBI, which was discussed in Section 2.2.2.1. This system uses a 0 to 9 scale to rate bridges and their components. This is not the only method used by states. Individual states have created their own methods to compare bridges under their supervision. Beyond the United States there are different methods being used by countries that use different ways of classifying distresses. The following sections will examine the methods used by individual states and countries.

2.4.2.1. New York State Bridge Rating System

New York State Department of Transportation (NYSDOT) has created a system for rating their bridges which is based on element level ratings and inspection. The system is based on a 1 to 7 scale which rates each element of the bridge (NYSDOT 1999). The different classifications are as follows:

- 7 – New Condition
- 5 – Minor Deterioration and is functioning as originally designed
- 3 – Serious Deterioration or not functioning as originally designed
- 1 – Potentially Hazardous

The rating scale also includes even numbers which are used when the element condition appears to be between two levels of classifications. Each element in the bridge receives a rating of 1 to 7. These items include the primary members, abutments, bearing pads, joints, bridge deck, etc. When multiples of an element type appear in a bridge, the worst rated of the individual elements is used in the bridge rating calculation. For example, if the bridge is a three span bridge the worst rated span of girders is used. Even if two of the spans have a rating of 7 and one span has a rating of 4, the one span rating of 4 becomes the rating for all of the spans of girders. In addition to the 1 to 7 ratings, elements are given a rating of 8 when the inspector is sure this element does not exist. It can also be rated a 9, which are essentially flags that mean the inspector is sure they exist, but is unable to visually inspect the element.

NYSDOT has a standard list of bridge elements that need to be checked during an inspection. Elements are also assigned a weight factor based on the elements' importance to the structure's load path that is used to calculate the bridge condition rating. Primary members receive a weight of 10, whereas the curbs only have a weight of 1. Other important elements, whose weight is an 8, are the pier columns, pier footings, abutment stem, and the structural deck.

To calculate the condition rating for the bridge, the sum of the element inspection ratings multiplied by their respective weights is divided by the sum of the respective weights. This is shown in Equation (11). This rating should be no less than the lowest rated element. A sample of the condition rating calculation is shown in Table 7.

$$\mathrm{CR} = \frac{\sum \mathrm{Wi} \times \mathrm{Ci}}{\sum \mathrm{Wi}} \tag{11}$$

Where,

CR = Condition Rating

Wi = Element Weighting Factors

Ci = Element Condition Rating

This method has been used at NYSDOT to effectively rate their bridges for use in their BMS. NYSDOT considers a bridge with a CR less than 5.0 to be structurally deficient and requiring MR&R action. Although it uses a similar method to rate each element, the calculation of the bridge condition is not solely based on the inspector's judgment. The inspector uses his experience to rate the individual elements, but the weights used allow the ratings to be combined into a health index that reflects which elements are in the worst shape. The use of weight factors also creates a uniform method of rating the bridges across the state.

Table 7: NYSDOT Bridge Rating Example (NYSDOT 1999)

INSPECTION ITEMS	INSPECTION RATINGS	WEIGHTING FACTORS
Main Structural Members	3	10
Abutments	5	8
Piers	8	8
Wingwalls	5	5
Bridge Seats	4	6
Backwalls	9	5
Bearings, Etc.	2	6
Structural Deck	3	8
Secondary Structural Members	8	5
Joints (Superstructure)	4	4
Wearing Surface and Joints	3	4
Curbs	5	1
Sidewalks and Fascias	5	2

$$\text{Condition Rating} = \frac{(3x10)+(5x8)+(5x5)+(4x6)+(2x6)+(3x8)+(4x4)+(3x4)+(5x1)+(5x2)}{10+8+5+6+6+8+4+4+1+2}$$

C.R. = 3.667

According to the NYSDOT website as of April 2009 approximately 12% of bridges were structurally deficient and 25% were functionally obsolete. The percentage of structurally deficient is on average with the rest of the nation. The American Society of Civil Engineers (ASCE) did not provide a report card on the state of New York, but since their percent structurally deficient is the national average it can be assumed that the grade is a C. New York faces many challenges in maintaining its bridge inventory due to a relatively long winter season and use of road deicers. These factors greatly affect the condition of the bridge. Although the number of structurally deficient bridges is not a direct representation of the condition rating system, the system can play a role in improving the ratings and the efficiency of maintenance tactics to counter deterioration.

The NYSDOT method can be effective for supporting the allocation of resources to not only deficient bridges, but also to those bridges that have very poor individual spans. Since the ratings take into account the worst element and generally not the entire bridge, it can allow engineers to target specific spans that need maintenance and repair since the rating represents the worst condition span. Replacing or repairing individual spans can be more cost effective than replacing or repairing the entire bridge.

2.4.2.2. California Bridge Health Index

The California Department of Transportation (CalTrans) is responsible for over 12,500 bridges across the state. CalTrans had previously used the Federal Sufficiency Rating (SR) as a way to classify the condition of their bridges. However, the department felt that the ratings did not meet the department needs for identifying the condition of the network or individual projects (Shepard and Johnson 2001). In an effort to develop a method of assessing the bridges condition based on economic worth, Caltrans decided to create their own methodology. The method is very simple in its design but can be a valuable tool in making maintenance and financial decisions for different bridges. The result of Caltrans efforts is a diagnostic tool called the California Bridge Health Index (CBHI).

The first step in the process is the completion of an element level inspection on the bridge. Quantities of each element are categorized into five condition states, 1 being like new and 5 being completely deteriorated. These inspection reports are done on a regular basis at the same time as CalTrans performs its NBI inspections.

The method takes the element level inspection and inventory data and applies the current cost of failure for each of the elements. Equations (12) through (15) are the basis to the rating method:

$$\text{HI} = \left(\frac{\sum \text{CEV}}{\sum \text{TEV}}\right) * 100 \quad (12)$$

$$\text{TEV} = \text{TEQ} * \text{FC} \quad (13)$$

$$\text{CEV} = \sum (\text{QCS}_i * \text{WF}_i) * \text{FC} \quad (14)$$

$$\text{WF} = [1 - (\text{Condition State \#} - 1)\left(\frac{1}{\text{State Count} - 1}\right)] \quad (15)$$

Where,

HI = Health Index

CEV = Current Element Value

TEV = Total Economic Value

TEQ = Total Element Quantity

FC = Failure Cost

QCS = Quantity in Condition State

WF = Weighting Factor for Condition State

The steps towards calculating each of these parameters are very similar. For the TEV (Equation 13) the total quantity of each element, independent of condition state, is multiplied by the unit failure cost of that element. The obtained value calculated represents the total value of the bridge based on what it would cost to replace all the elements.

To calculate the CEV of the bridge the unit cost is multiplied by a condition state weight factor as well as the quantity in each condition state, as shown in Equation (14). The weights are calculated using Equation (15), which uses the number of condition states for the element and what state is being investigated. For example steel girders with a condition state 1, which is like new condition, has a weight of 1 where a condition state 3 has a weight of 0.5. The weighted values, (QCS*WF), are then multiplied by the failure cost of the element type. These values are then summed together to get the CEV.

After CEV and TEV are calculated for each element they are summed together to get CEV and TEV values for the entire structure. These two values are then inserted into Equation (12) to calculate the bridge health index (BHI) of the structure. CalTrans uses a scale of 100 to classify the BHI for the bridge. This scale is preferred by CalTrans but could be adjusted to match any desired scale. Higher values of BHI represent a better condition bridge. Tables 8 through 10 show an example calculation of a bridge using the CBHI.

Table 8: Inspection Data for Sample Bridge (Shepard and Johnson 2001)

INSPECTION DATA FOR SAMPLE BRIDGE

Element Description	Units	Total Quantity	State 1	State 2	State 3	State 4	State 5	Unit Failure Cost (FC)
Concrete Deck	Sq. m	300	-	-	300	-	-	$600
Steel Girder	m	100	61	34	5	-	-	$3,500
R.C. Abutment	m	24	24	-	-	-	-	$7,700
R.C. Column	ea.	4	4	-	-	-	-	$9,000
Joint Seal	m	24	-	-	24	-	-	$556

Table 9: Total Element Value for Sample Bridge (Shepard and Johnson 2001)

TOTAL ELEMENT VALUE

Element Description	Calculation	Resulting TEV
Concrete Deck	300*600	$180,000
Steel Girder	100*3500	$350,000
R.C. Abutment	24*7700	$184,800
R.C. Column	4*9000	$36,000
Joint Seal	24*556	$13,344
	Total (∑ TEV)	$764,144

Table 10: Current Element Value for Sample Bridge (Shepard and Johnson 2001)

CURRENT ELEMENT VALUE

Element Description	Calculation	Resulting TEV	Element Health
Concrete Deck	300*0.5*600	$90,000	50.00
Steel Girder	[(61*1.0)+(34*0.75)+(5*0.5)]*3500	$311,500	89.00
R.C. Abutment	24*1.0*7700	$184,800	100.00
R.C. Column	4*1.0*9000	$36,000	100.00
Joint Seal	24*0.0*556	$0	0.00
	Total (∑ CEV)	$622,300	

The BHI for the sample bridge is calculated by dividing the CEV of $622,300 by the TEV of $764,144. The final BHI value for this bridge is 81.4. This represents that the bridge has retained 81.4% of its original economic value.

Bridges are then classified by their BHI into five condition states, ranking 1 to 5. These states are used in the selection criteria for different MR&R actions to be performed on the bridge. The following are the acceptable ranges of BHI:

Condition State 1: BHI = 100
Condition State 2: $90 \leq \text{BHI} < 100$
Condition State 3: $80 \leq \text{BHI} < 90$
Condition State 4: $70 \leq \text{BHI} < 80$
Condition State 5: $\text{BHI} < 70$

CalTrans uses these condition classifications to allocate funding to bridges with the most need. The BHI also has been used to track the effectiveness of different MR&R actions being used, determining the overall network health, the effects of different levels of funding on the network health, and measuring performance target levels. The current CalTrans goal is to have their bridges at a BHI of 80 or better. The department records each year the percentage of bridges that do not meet this goal and separate them by district. This allows engineers to see where problem areas are and to help allocate the necessary funds to help the district reach the target level.

The CBHI has shown to be an efficient method of calculating the health of a bridge. Pontis has even adopted a bridge health index module into its software package to calculate the BHI. The method helps to eliminate inspector subjectivity by requiring detailed ratings for each quantity of an element and not just one value for the entire element.

Sensitivity of CBHI to Element Failure Costs and Conditions

When using the CBHI one of the concerns is how failure cost can play a role in altering the ratings of bridges. Kang and Adams (2010) have researched this area in detail and their results show that the BHI is more sensitive to changes in condition than to changes in failure cost. However this does not mean that failure cost has no influence on bridge ratings.

Kang and Adams analyzed hundreds of bridges in Wisconsin and computed the element health index (HI) for each element in the bridge. The group looked at three scenarios for failure costs (FC) of bridge elements: a range of ±10% of FC, ±20% of FC, and ±50% of FC. The baseline failure cost was calculated for each element using a method presented by Al-Wazeer. Element level bridge inspection data for 1601 inspection reports on 221 simple span and continuous prestressed concrete bridges were used in the project. The analysis changed the FC for each element by a random interval within the previously mentioned thresholds. For each bridge the element conditions were kept constant. The simulation generated approximately 1,000 random FC for each element range, providing a total of 3,000 FCs for a single element. The varying values of FC provided a total of 3,000 different BHI ratings for each bridge.

The results of this analysis showed that as the range of FC extends to ±50% the variation in a baseline BHI of 85 was approximately ±3 points for simple span bridges and ±4 for continuous bridges. These results are shown in Table 11 which summarizes the results and Figure 9 which is an example of the results for simple span bridges. These results show that there is not much variation in BHI if the FC is changing and element condition is the same, but as the bridge baseline BHI becomes lower the variation in rating due to failure cost increases linearly. If the trend continues a baseline BHI of 50 could vary by as much as ±10 points. This could be a major difference when trying to allocate funds. As one district's FC could show a bridge rated a 60 and a bridge in the same condition in another district could be rated a 40. Funding will be first allocated to the district which uses a FC that causes the appearance that their bridges are in seemingly worse condition.

Table 11: Interval between Upper and Lower Limits for Deterministic BHIs by Various Element FCs (Kang and Adams 2010)

DECK TYPE	FAILURE COST ESTIMATE	INTERVAL (% change of deterministic BHI		
		85	90	95
Prestressed Concrete Deck	±10%	1.4 (1.6%)	0.9 (1.0%)	0.5 (0.5%)
	±20%	2.7 (3.2%)	1.8 (2.0%)	0.9 (1.0%)
	±50%	5.9 (7.0%)	4.0 (4.4%)	2.0 (2.1%)
Continuous Prestressed Concrete Deck	±10%	1.5 (1.8%)	1.0 (1.1%)	0.5 (0.5%)
	±20%	3.0 (3.6%)	2.0 (2.3%)	1.0 (1.1%)
	±50%	7.7 (9.1%)	5.2 (5.7%)	2.6 (2.8%)

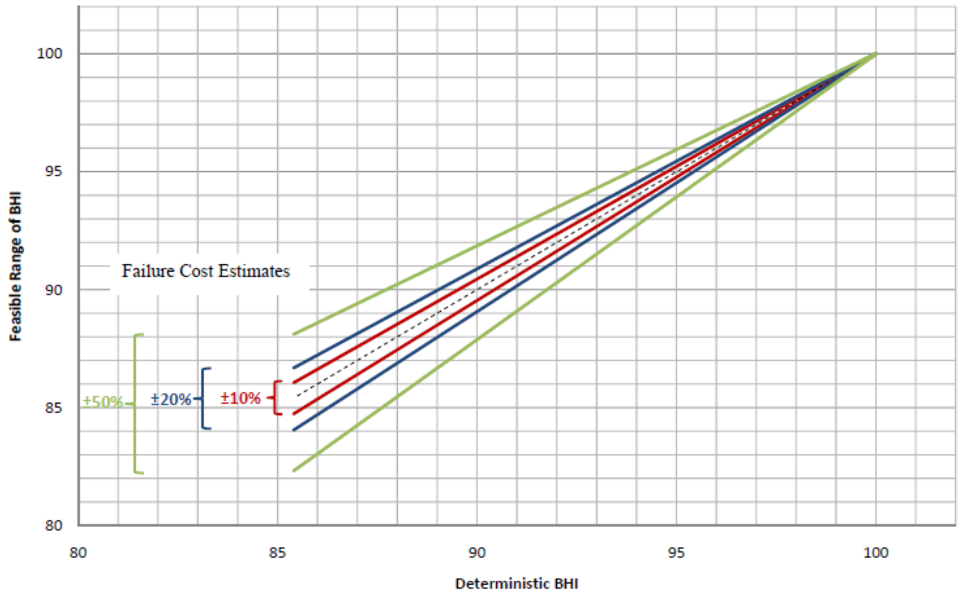

Figure 9: Sensitivity Analysis of Prestressed Concrete Deck Bridges to Variation in FC Estimates (Kang and Adams 2010)

The second part of Kang and Adams' study was to analyze how BHI varies as the element condition changes and the FC stays the same for all the elements. The same ranges of ±10%, ±20%, and ±50% were used in the changes for condition state. Figure 10 shows an example of how the conditions were changed. The changes were done by taking 10%, 20% or 50% of a quantity in each condition state and shifting them up or down one condition state.

Figure 10: Method of Reducing Element Condition (Kang and Adams 2010)

Example 1. If -10% is selected (bridge condition would be worse)

Original element quantities					
C1	C2	C3	C4	C5	Total
29	26	9	3	0	67

10% (2.9) 10% (2.6) 10% (0.9) 10% (0.3)

Perturbed					
C1	C2	C3	C4	C5	Total
29- 2.9 =26.1	26- 2.6 +2.9 =26.3	9-0.9 +2.6 =10.7	3- 0.3 +0.9 =3.6	0+0.3 =0.3	67

The analysis showed that varying the element condition caused greater variation the overall BHI of a bridge than by adjusting failure cost. Table 12 and Figure 11 show these results. BHI varied more from the baseline BHI values calculate with the original FC and condition values when the condition was reduced by the allowable ranges. For a reduction in element condition of 50% a baseline rating of 85 changed to a 73, a 12 point difference. This shows that the method of CBHI is more sensitive to changes in element condition than to the failure cost used in the analysis.

Although this study shows that element condition causes greater variation in BHI than failure cost, it was shown that failure cost can vary the bridge ratings produced using this method. As stated in section 3.3.2.1 a goal of this thesis was to eliminate any fluctuation in rating caused by changes in failure cost. A variation of ±4 points for all the structures in a corridor due to failure cost can increase the rating of a section and can have consequences in funding allocation. For that reason, the use of element weights that can be applied for all corridors will be employed in this thesis to eliminate this fluctuation.

Table 12: Interval between Upper and Lower Limits for Deterministic BHIs by Various Element Conditions (Kang and Adams 2010)

DECK TYPE	FAILURE COST ESTIMATE	DETERMINISTIC BHI			
		85	90	95	100
Prestressed Concrete Deck	±10%	3.3 (3.9%)	3.0 (3.4%)	2.7 (2.9%)	2.4 (2.4%)
	±20%	6.7 (7.8%)	6.1 (6.7%)	5.5 (5.8%)	4.9 (4.9%)
	±50%	16.6 (19.6%)	15.2 (16.8%)	13.7 (14.4%)	12.2 (12.2%)
Continuous Prestressed Concrete Deck	±10%	3.4 (4.0%)	3.1 (3.4%)	2.7 (2.9%)	2.4 (2.4%)
	±20%	6.9 (8.1%)	6.2 (6.9%)	5.5 (5.8%)	4.8 (4.8%)
	±50%	17.2 (20.3%)	15.5 (17.2%)	13.7 (14.4%)	12.0 (12.0%)

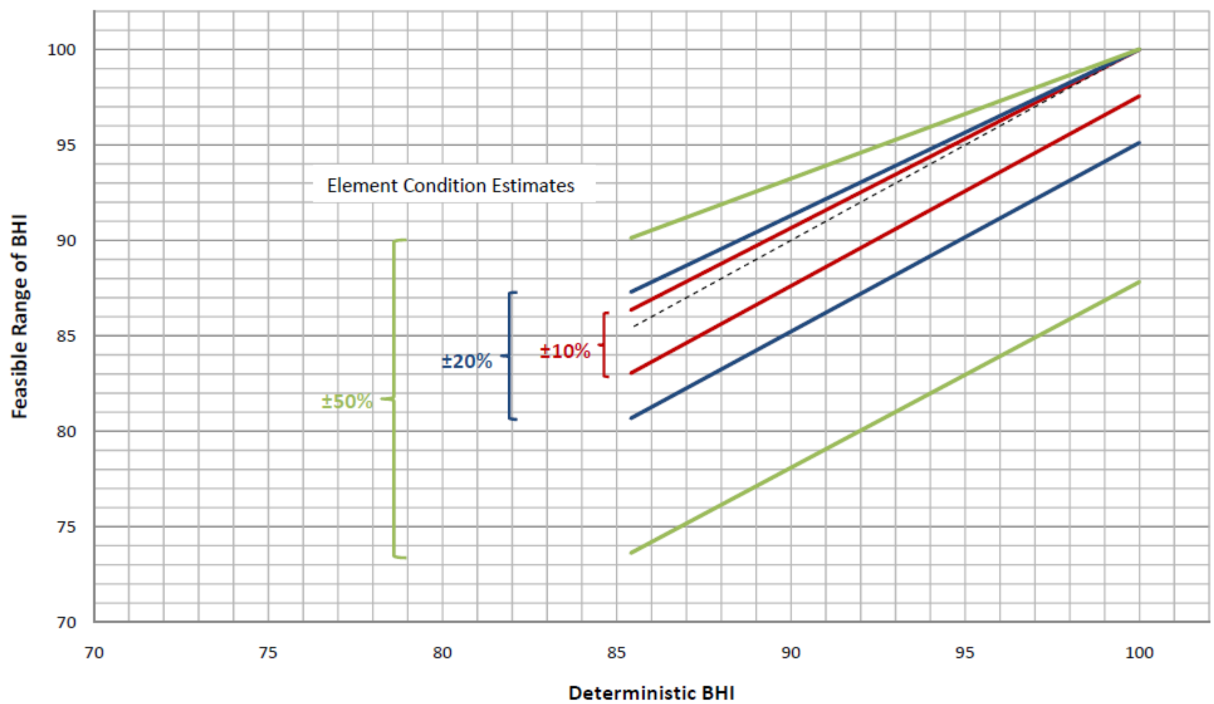

Figure 11: Sensitivity Analysis of Prestressed Concrete Deck Bridges to Variation in Element Condition (Kang and Adams 2010)

2.4.2.3. Finland Bridge Repair Index

The Finnish Road Administration (Finnra) is the governing organization in charge of the road network in Finland. Finland has a network of 20,000 bridges that have a total bridge deck area of 36.6 million ft^2 and 208 miles in length (Hearn et al 2005). Finnra is responsible for approximately 11,000 road bridges throughout the country. Finnra is charged with the task of maintaining their bridges and keeping them both structurally and functionally sufficient.

To meet this task, Finnra has created a bridge repair index (KTI) and a rehabilitation and replacement index (UTI). These indices take current bridge condition and inspection information and inserts them into an equation to determine which structures are in need of MR&R actions. Higher scores reflect more need.

The KTI incorporates four factors in its equation: condition of the element, urgency of the repair, severity of the damage, and the weight of the element. The weight of the element is set by Finnra and represents the elements importance to the structural load path. To determine KTI, each element receives a grade calculated by multiplying the four factors. The maximum value is then obtained and added to the weighted sum of grades of the remaining elements. This is shown in Equation (16).

$$KTI = \max(Wt_i \times C_i \times U_i \times D_i) + k \sum (Wt_j \times C_j \times U_j \times D_j) \quad (16)$$

Where,

KTI = Repair Index

Wt = Weight of the damaged element

C = Condition of the element

U = Urgency of the repair

D = Severity of Damage

k = Weight for damage summation. Default is 0.2.

i = Worst defect

j = Other defects

Inspectors rate each element with a value for C, U, and D. Finnra provides inspectors with a table for each which explains the damage and provides points to be used in Equation (16). Tables 13 through 16 provide values for all four factors listed in Equation (16).

Table 13: KTI Element Weights (Hearn et al 2005)

Bridge Element	**Wt**
Substructure	0.70
Edge Beam	0.20
Superstructure	1.00
Overlay	0.30
Other surface structure	0.50
Railings	0.40
Expansion Joints	0.20
Other equipment	0.20
Bridge Site	0.30

Table 14: KTI Condition Points (Hearn et al 2005)

Condition Ratings	Condition Points, C
0 - New or Like New	1
1 - Good	2
2 - Satisfactory	4
3 - Poor	7
4 - Very Poor	11

Table 15: KTI Repair Urgency (Hearn et al 2005)

Repair Class	Repair Urgency Points, U
11 - Repair during next 2 years	10
12 - Repair during next 4 years	5
13 - Repair in the future	1

Table 16: KTI Damage Points (Hearn et al 2005)

Damage Class	Damage Severity Points, D
1 - Mild	1
2 - Moderate	2
3 - Serious	4
4 - Very Serious	7

Finnra inspectors use the tables to classify the damage for each element. Finnra also adjusts the values to account for a bridge's importance. This is measured in the amount of traffic the bridge carries in a day. The Average Daily Traffic (ADT) is recorded for each bridge and the amount of ADT is used to scale the KTI value. Table 17 shows the factors that are multiplied by the KTI to get the corrected KTI value used in the ranking.

Table 17: KTI Daily Traffic Adjustment Factors (Hearn et al 2005)

ADT (Vehicles/Day)	Factor
> 6000	1.15
3000 - 6000	1.10
1500 - 3000	1.00
350 - 1500	0.90
< 350	0.85

In addition to the KTI ranking index Finnra uses the UTI to rank the bridges qualifications for rehabilitation or replacement. The determination of UTI uses factors of condition, load capacity, functionality, bridge total area, and ADT. Tables for these factors were not presented in the literature (Hearn et al 2005), but the equation used is shown in Equation (17).

$$UTI = kp \times kl \times (\text{Condition} + \text{Load Capacity} + \text{Functionality}) \qquad (17)$$

Where,

kp = Factor for total bridge deck area

kl = Factor for ADT on bridge

Finnra uses both indices to keep their network at a sufficient condition level. The indices do not provide engineers with a bridge condition rating, such as the NYSDOT or CBHI methods do, but a rating that reflects the bridge's need to be repaired. They provide engineers with a method of identifying poor bridges that need the most attention and trigger what MR&R actions need to be performed on each bridge based on repair urgency.

The benefit of a method such as Finnra's is that if a limited budget is available to the agency, it can use the indices to identify which projects the money could benefit most. Finnra uses the two to help prioritize projects within its BMS. This condition rating method has proven effective for Finnra and will be their main rating method in the foreseeable future.

2.4.2.4. South Africa Bridge Condition Ratings

The South African National Roads Agency (SANRAL) is the main government agency in charge of the country's roads and bridges. They maintain the network of roads called "trunk roads" which are the equivalent of the NHS in the United States. Trunk roads carry approximately 70% of the VMTs in the country and contain 4,800 miles of roads and 2,100 bridges (Hearn et al 2005). In addition to the roadways, South Africa has approximately 10,000 railway bridges in its network. This section will focus on the highway bridges under the control of SANRAL.

To maintain the condition of the highway bridges, SANRAL has developed a set of performance indicators that are based on data from the South African bridge reporting system. In this system each defect in the bridge has its degree, extent, and relevancy (DER) reported. Raters rate each defect for DER on a scale of 0 to 4, 0 being no defect and 4 being critical defect. Table 18 summarizes the DER Rating Values.

Table 18: Summary of DER Rating Values (Hearn et al 2005)

	Degree, D	Extent, E	Relevancy, R	Urgency
0	None			Monitor Only
1	Minor	Local	Minimum	Routine
2	Fair	> Local	Moderate	< 5 years
3	Poor	< General	Major	< 2 years
4	Severe	General	Critical	ASAP

Each defect is rated with the DER values. Once these values are obtained, South Africa uses a performance indicator equation to obtain the bridge condition. For each defect a condition rating is calculated using Equation (18). The equation uses the 0 to 4 values for D, E, and R. These values do not need to be equal. For example a defect could be small amounts of severe cracking in a localized area and be of moderate relevancy. Therefore the D would equal 4, E would equal 1, and R would equal 2. Table 18 is just a summary of the 0 to 4 scale for each measure.

$$I_c = 100\left[1 - \frac{(D+E)R}{32}\right] \qquad (18)$$

Where,

I_c = Condition Index

D = Degree of defect

E = Extent of defect

R = Relevancy of defect

Higher I_c values represent a less critical defect. If the DER values are all 0 then the I_c is 100. If the DER values are all 4 then the I_c is 0. This equation is applied to all of the defects found on the bridge.

After all of the defect values are calculated, they are summed together to be used in the bridge condition index (BCI) for a network of bridges, which is calculated as the sum of the condition indices for a bridge weighted by the percent of the total network ADT carried by the bridge.

Equation (19) shows the calculation of BCI. Higher BCI values represent a better condition bridge and low values show a deteriorated bridge. These values can be used to allocate funds within the network.

$$BCI_n = \frac{(\sum_j Ic_j)ADT_n}{\sum_i ADT_i} \tag{19}$$

Where,

BCI_n = Bridge Condition Index for bridge n

$\sum Ic_j$ = Summation of I_c for all defects in bridge n

ADT_n = Average Daily Traffic for bridge n

$\sum ADT_i$ = Summation of Average Daily Traffic for i bridges in the network

The BCI provides SANRAL with a ranking system within a bridge network that account for both the importance of the defects and the importance to travelers. One issue is that the use of ADT has been shown to increase the BCI for heavily travelled bridges (Hearn et al 2005). If the bridge carries a very large percentage of network traffic, it could increase the BCI to a point where the condition appears to be much higher. Two bridges could have the same summation of defects, but the more travelled bridge will appear to be in better condition because of the higher traffic. It would seems the system would be more appropriate if the amount of traffic decreases the BCI, showing that the bridge is more important to maintain and should have more focus.

This system does however provide SANRAL with a reliable method that is not difficult to use and can be used for network evaluations. SANRAL then uses the BCI as part of its repair prioritization process. They use an optimization process which seeks the group of projects which will reduce the defect relevancy, R, the most for a certain budget.

2.5. *Literature Review Summary*

The practice of asset management has been used effectively to help analyze, manage, develop MR&R programs, and budget funds for different roadway assets. IMS are very similar across the nation in the functions they can perform. Using these programs, engineers are able to manage large networks of pavements, bridges, and other assets.

Although the IMS are similar the data used to run these systems can vary from state to state. Condition rating systems for pavements and bridges lack the consistency and sensitivity to appropriately compare ratings of assets between states and between countries. Currently in practice there are several condition rating methods that can show the health of an asset and properly display the changes to the asset as it ages and is exposed to traffic.

These current condition rating systems can be used at a national level with some adjustments to incorporate data used across the nation. With modified versions of current methods it is possible that individual asset ratings can be combined if they have rating methods that follow the same pattern and scale.

CHAPTER 3: **Generic Methodology Framework**

This chapter discusses the general methodology used to create health indexes for use pavement and bridge evaluation at the corridor level. It is based on a flexible framework that can be customized to meet the specific needs of various agencies.

3.1. *Purpose of the Methodology*

When deciding on the proper data and evaluation techniques to be used the following goals were considered:

- Use of data currently collected by a high percentage of State Agencies.
- Ability to customize data input parameters without changing overall methodology.
- Ability to customize data transformation equations without changing overall methodology.
- Scale that is common among the assets.
- Method that follows similar patterns between assets.
- Use of Weighted Values to accurately rate asset based on individual element conditions.
- Method should be expandable to other type of assets

The literature reviews in Chapter 2 identified current data and methods employed across the United States. Some of these data items and methods were used in the development of this framework. These goals were set not only to base a new method on already available data items and proven methods, but also to allow flexibility in its use. The overall goal was to develop a method that could be adapted to include new data as it became more readily available, or to adapt a more appropriate rating scale. The following sections will describe the procedures used in the development of the framework. This includes generic equations that can be applied to each asset, basic principles, and terminology that will be common among all assets.

3.2. ***Health Index Framework***

The overall goal of the thesis is to develop a framework to rate all assets contained within a corridor section with a single condition rating value. This would be done by combining condition rating values for each asset type within the corridor into a single corridor condition index. The assets could include, but are not limited to, pavements, bridges, railways, toll plazas, weigh stations, pavement markings, safety features, etc. Figure 12 displays the general framework.

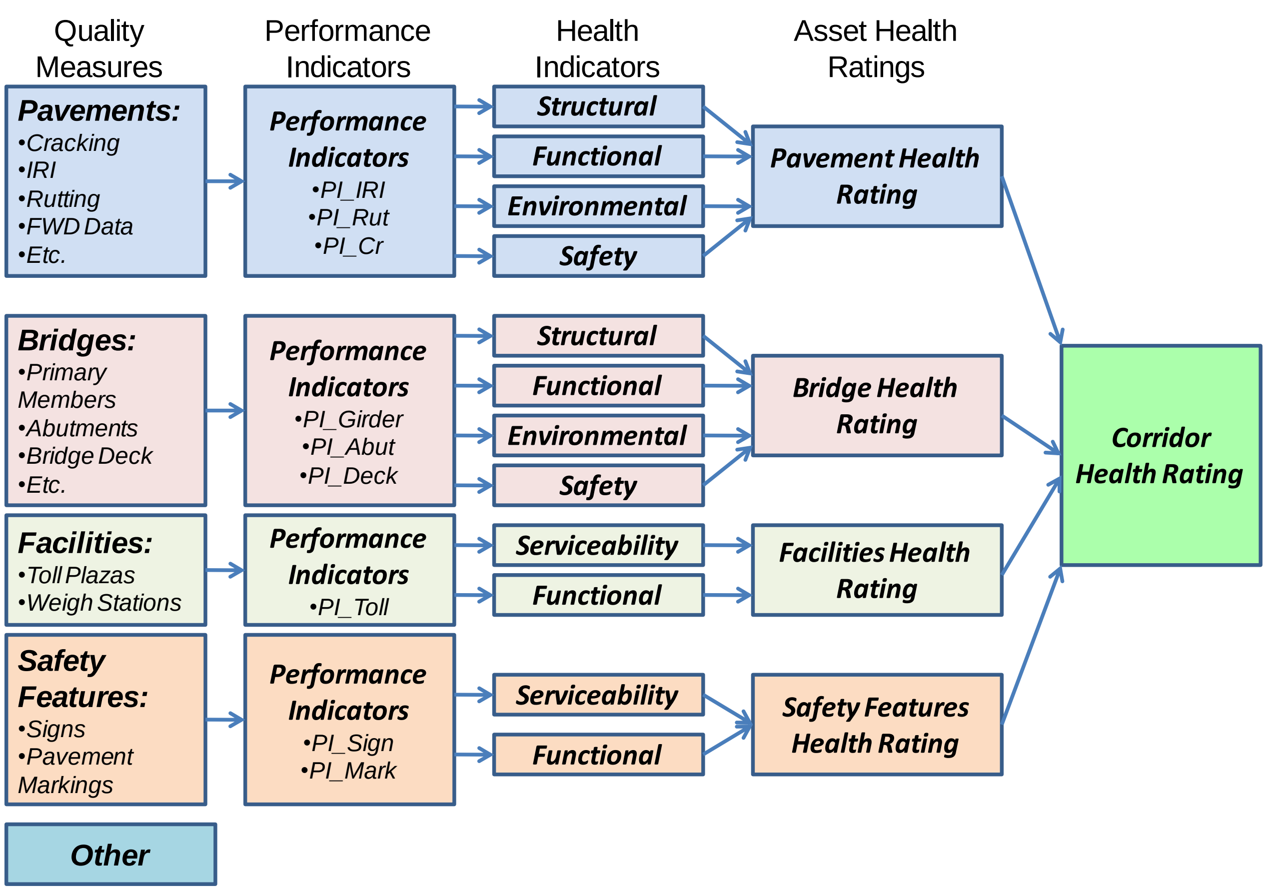

Figure 12: Generalized Framework for Corridor Health Rating Methodology

To reach the final condition rating for the corridor there will be different levels of detail that will be calculated. The first step is to transform the measured data (quality measures) into a performance indicator. Each of these performance indicators will receive a rating which represents the amount of distress/deterioration in the asset (i.e. Roughness, Bridge elements).

Performance indicators are then grouped into health indicators. These health indicators represent the health of the asset in various areas; structural, functional, safety, environmental, serviceability, etc. Health indicators can include any number of performance indicators. Performance indicators can also be used in more than one health indicator. For example, rutting can influence both the functional and structural health indicators of pavement and is used in the calculation of both indicators.

Once the health indicators are calculated the values can be combined to calculate the asset health rating. Each health indicator is given a weight to represent its overall importance to the asset health. This asset health rating would reflect the overall condition of the bridge as a function of the performance in the different health indicators previously mentioned.

The next level of aggregation would be the overall asset health rating. This value would combine the individual assets into a single health rating for the asset. This value would be of the same scale as the individual indicators. Each health indicator would be assigned a weight to show its importance to the overall condition of the asset in the section. The ratings would be a representation of the overall condition of the asset.

The last level of aggregation would be the combination of individual asset health ratings into the overall corridor health rating. This value will depend on the health of every asset contained within the corridor of interest. Individual asset health ratings would be weighted as a percentage of the overall cost to replace the asset. For example if the cost to replace all the bridges in a section comprises 20% of the total cost to replace, then the bridge rating would be multiplied by 0.20. Percentages would be calculated for each asset and multiplied by its respective asset rating. These would then be summed to obtain the corridor health rating.

The ratings produced from this framework will describe the conditions of individual assets (e.g. Pavement Health Rating) and the overall Corridor Health Rating. These values can be reported to FHWA to allow them to identify sections where the condition of all physical assets are very low and are in need of MR&R action.

The general framework shown in Figure 12 is the ideal version that includes all of the classifications. However, for this project only structural and functional health indicators will be considered. There is an overall lack of data for the other health indicators that makes it impractical to use at this time.

3.3. ***Selection of a Rating Scale***

The first step in the development of the framework was to select a rating scale for the evaluation of individual assets. A common rating scale applicable to all assets was chosen to allow a simpler combination of the assets into one condition rating.

A common scale allows for a more feasible combination of the individual rating systems. There was much debate over which scale should be used. Some of the possible scales considered were 0 to 5, 0 to 10, 0 to 100, Letter Grade A, B, C, D, F, or even a 0 to 50. Each scale had its advantages and disadvantages. A small scale, for example 0 to 5, allows easy distinctions between values if integer ratings are used. However, the disadvantage is that value it does not provide enough rating options and therefore might not be able to distinguish between different asset conditions. For example, assets with a rating of 3.51 and 4.49 will both be classified as a 4. There is a very large gap in the condition of these two assets that does not get properly displayed on such a small scale.

A larger scale from 0 to 100 can help to eliminate this variation in condition at different values. This scale is used in academic settings due to its ability to distinguish between closely ranked students. It has been used by state agencies for the same reason. Fund allocation to individual projects is based on the current condition of the asset. The need for a detailed rating scale stems from the need to distinguish between similarly rated projects to make sure the worst condition asset receives more attention and funding. A 0 to 100 scale is a good way to make these distinctions.

Although a scale of 0 to 100 would give great detail for individual projects, it was decided for this project that it was too detailed for a rating scale to be used to support strategic decisions. For use in comparing assets or sections at the network or corridor level, it was decided that a scale of 0 to 10 would adequately describe the general condition of the sections. It provides enough detail to differentiate between an 8 and a 10, but is not too detailed where a decision would not be between an 88 and an 87. Therefore, it was decided that a scale of 0 to 10 would be the basis of the methodology.

This base scale was determined for this project to allow the researchers to calculate reasonable values in a methodology application example. Should the methodology be employed the scale could easily be customized to adapt to the needs of the governing agency.

3.4. *Data Collection*

A major factor required for successful nation-wide implementation of the proposed methodology is to incorporate data that is collected by the majority if not all states. Therefore, the pilot implementation of the methodology presented in this thesis uses data which is currently being collected by every state. For example, HPMS requires the reporting of a number of pavement distresses on a regular basis. These can be used as the base quality measures to be used for pavements.

3.5. *Generalized Methodology Development*

This section covers the equations and input variables that are common among assets. It describes all the steps from the data transformation all the way up to the determination of the final corridor health rating.

3.5.1. **Performance Indicators**

The methodology starts with the calculation of performance indicators (PI) based on the collected data (quality measures). The performance indicators are values on which describe how each element, distress, portion, etc. of an asset is performing. The PI should reflect the remaining usable life of an item. As each asset uses different measures of performance the PI calculation for individual assets will be different for each asset. This is the only phase of the asset rating calculation that is asset dependent.

3.5.2. **Health Indicators**

The health indicator (HI) of an asset is a measure of the asset's ability to perform its basic function. It typically includes several performance measures such as ride quality, lane clearances, height restrictions, etc. For the proposed framework, the HI will be used to rate the individual asset's performance in one of four performance areas; functional, structural, environmental and safety.

The HI rating is measured on a scale of 0 to 10. The rating is a weighted average of relevant PI values. For example, pavement functional health indicator (FHI) is influenced by items which change the ride quality of the surface such as roughness, rutting, bleeding, and texture. Bad PI ratings of these data items can cause discomfort to the user as they drive, decreasing the FHI of the pavement.

The calculation of HI based on the COST methodology was also evaluated. This method is shown in Equation (9). This method takes worst case scenario for the condition of the CPI values used in the COST methodology. Using this method means that the overall condition will be worse than the condition of the worse PI value. With the proposed weighted average method the FHI value will be within the range of the highest and lowest PI values.

With both the COST and proposed methodology procedures the condition of the HI will be calculated, but the results will be different. For example if one distress has a bad PI value and has a high weight, the overall HI could reach zero if using the COST Method. The addition of other PI values will lower the rating even if these distresses are low. In the weighted average method the rating will be slightly raised if the other PI values are performing well.

For this project the COST Method was not used to combine PI into the HI. The reason being that the change in scale caused the equations to need adjusting. With COST the higher values indicate bad condition. In the proposed scale higher values indicate good condition. If equation (9) is used with subtraction instead of addition, the good PI values will lower the condition of the HI more than the bad PI values. Therefore, the COST method was not used. The COST method for HI could be used but the equations will need to be redone to account for the change in scale. The COST method could be considered as another alternative.

To calculate the HI each PI is multiplied by its respective weight. All weighted PI values are summed and divided by the sum of the weights. This calculation is summarized in Equation (20).

$$HI = \frac{\sum PI_i * W_i}{\sum W_i} \qquad (20)$$

Where,

HI = Health Indicator

PI_i = PI Rating for each distress

W_i = Weight of PI for each distress

Using the weighted average has the advantage that more PI values can be easily added to the calculation of a HI value as more quality measures are collected. Adjustment of the PI weights will make the addition of these values possible. Considering HI can help to make engineers aware of the different quality measures that affect the performance of an asset in the different areas.

3.5.3. **Individual Asset Health Rating**

The next step in the framework is to calculate the rating of individual assets. The rating will be a combination of the health indicators.

The equation to calculate the asset health rating (AHR) for each individual asset is:

$$ARH_i = \frac{\sum HI_j * W_j}{\sum W_j} \tag{21}$$

Where,

ARH_i = Asset Rating for Asset "i"

HI_j = Health Indicator Type "j"

W_j = Weight Value for Health Indicator Type "j"

Each asset type will have different weight values for each health indicator depending on which health indicators are considered more critical for that asset. Use of this rating provides engineers and planners with a value that shows the overall condition of the asset by combining its health indicators.

3.5.4. **Overall Asset Health Rating**

One of the goals of the project was to create a method which followed a similar procedure between assets. To reach this goal, each asset used a similar method to combine individual asset health ratings into a single network value. This was done by multiplying the rating for each asset by its quantity (length of lane, bridge deck area, number of stations, etc.). For example, the individual pavement section area was multiplied by the individual pavement health ratings. These values for all the sections were added together and then divided by the total area of the sections. This provided an area-weighted rating for the entire section. This same method was done with the bridge ratings, the individual ratings were weighted by their respective deck area.

Using an area-weighted method was employed since it applies most importance to individual assets of larger size. For example, for pavements the measured sections in the example application discussed in Chapter 5 varied from 0.02 miles in length to 0.10 miles in length. There was not much variation and the area-weighted method overall rating was similar to the pure average of all the individual ratings, but a weighted method is preferred because it will eliminate any variation caused by different individual section sizes. The same holds true for bridges. Larger bridges are more costly to maintain and repair; therefore their rating should hold more weight. The bridge decks varied from 400 square feet to over 1,800 square feet. This variation in size needed to be accounted for.

Using an area-weighted method provided the way to eliminate variations caused by varying sizes of assets. In developing the methodology the pure average of individual asset ratings was checked to see the variance with the weighted average. The weighted average and pure average only varied slightly. However weighted average is still the preferred method since it will add more weight if there is more variety in asset size.

The individual asset ratings are used to calculate the overall condition of a single asset type contained in the corridor section. This value indicates how well the entire network of the asset type is performing.

To calculate the overall AHR for a corridor section, an area-weighted method was chosen. This method ensures that bad ratings on smaller assets do not carry as much weight on the overall rating. Although the condition of every asset in the corridor section is important, the overall condition of the corridor section should be more dependent on the condition of the larger assets as they are generally more costly to repair.

To calculate AHR, the rating of each asset is first multiplied by the quantity of the asset. These values are summed together and divided by the total quantity of the asset in the corridor section. This calculation is shown in Equation (22).

$$\mathrm{AHR} = \frac{\sum \mathrm{AHR_i} * \mathrm{Q_i}}{\sum \mathrm{Q_i}} \tag{22}$$

Where,

AHR = Overall Asset Health Rating for Corridor Section

AHR_i = Asset Health Rating of Individual Asset

Q_i = Quantity of Individual Asset (e.g. length, area)

Using the AHR for each asset type can provide a summary of the condition for each asset type within the section. This level of detail can tell engineers which asset type is in need of MR&R. This rating can be most effective as a communication tool to help describe the health of roadway assets to the public and government officials in charge of allocating funds to roadway projects.

3.5.5. **Overall Corridor Health Rating Methodology**

The final phase in the calculation of the overall corridor health rating (CHR) is to combine all the AHR values. The purpose of the Corridor Health Rating (CHR) is to provide a single value to compare the overall condition of all assets within a section of IHS and surrounding routes to other sections across the United States. No such combination of ratings is currently being used in the U.S. Different methods to combine the AHR were investigated. All are based on taking a weighted average of the individual AHR. Weighted average was the preferred method from the start of the project, but even the values of the weighting factor could vary greatly. It could be weighted based on the consequences of failure of each asset, the surface area of each asset, cost of each asset, percent weighted option, etc.

Several methods were considered before the final decision was made. The first method was to take the rating of each asset and assign it a percentage of the final rating. For example, the pavement health rating (PHR) would comprise 30-40% of the CHR and the bridge health rating (BHR) would fill the remaining percentage. This general equation is shown in equation (23).

$$\mathrm{CHR} = \sum \mathrm{W_i} * \mathrm{AHR_i} \qquad (23)$$

Where,

CHR = Corridor Health Rating

W_i = Weight of Asset Type "i"

AHR_i = Asset Health Rating of Asset Type "i"

This method provides a simple combination that could be used to provide a single rating. However, this method does not take into account the difference in the extent of the various assets. A section with more bridges should have more influence added to the BHR than a section on mostly pavement with few bridges.

The investigated second potential method takes into account the extent of each asset in the form of an area-weighted average. This option would include the influence of the ratio of the different areas and provide more weight to the larger area asset. This method is demonstrated in Equation (24).

$$\mathrm{CHR} = \frac{\sum Q_i * AHR_i}{\sum Q_i} \tag{24}$$

Where,

CHR = Corridor Health Rating

Q_i = Quantity of Asset Type "i"

AHR_i = Asset Health Rating of Asset Type "i"

The issue with this method of combination is that all asset types need to have the same measure for their quantity. This is feasible but is very difficult and may not be effective. For example, all assets could be quantified by square footage, but for some assets this may not be the best way to quantify. A major factor when deciding which corridor sections are in need of more funding is the current cost to replace a unit of each asset. Since these ratings will likely be used over many years, the cost to replace for an asset could change depending on the economy. Prices for asphalt, concrete, and steel can fluctuate greatly over a two year period. Including the current price of materials when the rating is reported will add greater influence to the asset which would cost more to replace. Therefore, the second method for combining asset ratings was adjusted to include the cost.

The cost used to calculate the final condition rating is the cost to replace one unit of the asset type. For example, the cost for pavement is the cost to replace one lane-mile. These costs have different units associated with each asset, therefore the cost values needed to be consolidated into the proper units so that the final rating results in a unit-less number. To achieve this, a coefficient was created to be multiplied with each AHR value. Each coefficient is a fraction of the cost to replace all of a single asset type in a section divided by the summation of all assets' cost to replace. To calculate a single asset's cost to replace the unit cost per quantity of an asset is multiplied by the total quantity of the asset contained in the corridor section. Therefore, the coefficient represents a percentage of the total cost of the section. Equations (25) and (26) show the final method used for this project.

$$\text{CHR} = \sum \text{C}_i\text{*AHR}_i \tag{25}$$

$$\text{C}_i = \frac{\text{Q}_i\text{*CostAsset}_i}{\sum \text{Q}_i\text{*CostAsset}_i} \tag{26}$$

Where,

CHR = Corridor Health Rating

C_i = Cost Coefficient for Asset Type "i"

AHR_i = Asset Health Rating for Asset Type "i"

Q_i = Total Quantity of Asset Type "i" for Corridor Section

$CostAsset_i$ = Cost to Replace Single Unit of Asset Type "i"

Using the cost coefficient will give more weight to the sections which will need more funds to improve the overall condition of the assets. For example, if the prices of concrete and steel increase and asphalt prices reduce, the bridge health rating (BHR) will have more influence on the overall condition of the section. If the section has a higher BHR than other AHR values with the previous cost scenario, the section will require less money to repair only the pavement in the section. Agencies can decide on the frequency of updating the index for changes in cost. The use of cost to replace and total quantity for each asset was selected as the final method of combining the individual AHR values for a given section. This equation is flexible enough, however, to add more assets if it is desired. Equations (25) and (26) would only need to have additional terms added. Also the coefficients for all the assets will change as the denominator will need to add the asset size multiplied by asset cost for the new asset.

3.6. *Condition Rating Summary and Conclusions*

The health ratings methodologies developed for the individual asset types and the overall corridor sections were developed to provide an objective methodology for determining the current health of a corridor section. The goal in their development was to provide a consistent method of aggregating data, use of nationally collected data, and provide flexibility to add new assets and quality measures. The goals were constantly considered during the development and were met. The steps provided in this chapter demonstrate the basis for a flexible method that can be used by to show the health of IHS sections. This methodology could prove to be an invaluable tool to engineers, planners and policy makers as it provides a straight forward way to show the condition and health of travel corridors throughout the United States.

CHAPTER 4: **Example Customization of Method to VA Data**

The following chapter will describes a pilot application of the methodology proposed in Chapter 3. The method is applied using data provided by VDOT to show the flexibility of the proposed framework. The chapter discusses the specifications used in conjunction with the VDOT data and the steps conducted to customize the health indices.

4.1. *Application to Pavement and Bridges*

The pilot application of the proposed health rating methodology focuses on pavement and bridge assets. These two categories of assets are the most significant in terms of asset value and have the most readily available data. Figure 13 highlights the part of the framework demonstrated in this thesis.

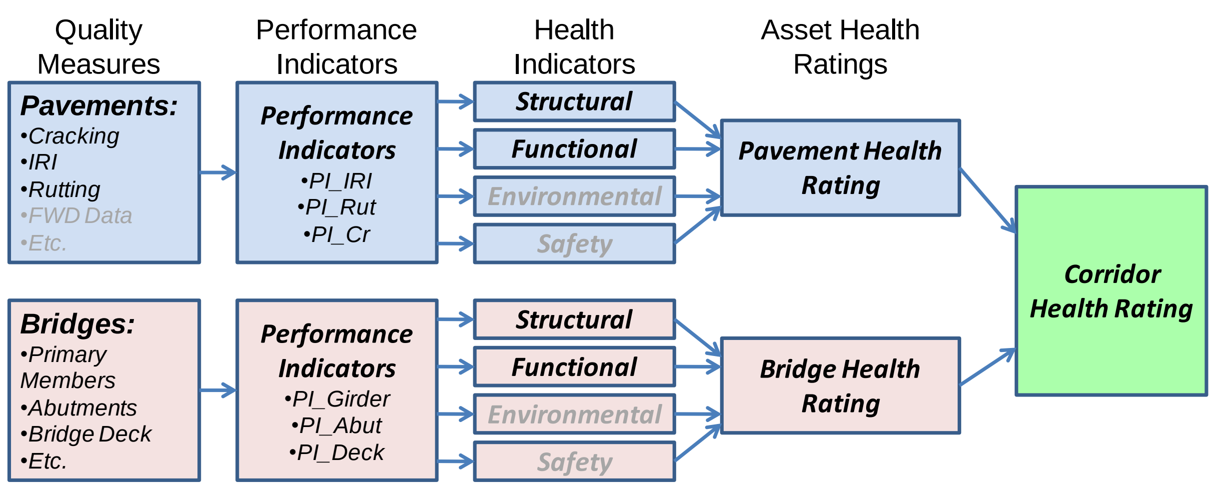

Figure 13: Framework of Customized Methodology using VDOT Data

4.2. *Pavement Health Rating Methodology*

For pavements the method uses measured data for sections of pavements and creates a rating for each quality measure. The COST approach was adjusted in order to meet our scale type and to incorporate the data that is readily available at state agencies across the United States. The scale was changed from that used in the COST Method, which required changes to the transfer functions to achieve the same scale. The proposed pavement methodology has also altered the combination of individual distress ratings to the methods described in chapter 3. The following sections discuss the variables used in the equations of chapter 3 for pavement assets.

4.2.1. **Data Collection**

For pavement, the data required to be reported as part of the HPMS (Section 2.2.1.1) was used for pavement assets. For calculating the health of the pavement section, the following data items provided by VDOT were used:

- International Roughness Index (IRI)
- Cracking
    - Alligator
    - Longitudinal
    - Transverse
- Rut Depth (Wire Method used to measure depth)

This data is currently collected by all states and therefore the method can be applied throughout the U.S. without additional effort or funding for data collection. However, the method is flexible enough that each state can further incorporate any additional data they specifically collect if they deem it necessary.

4.2.2. **Transfer Functions**

The major step in calculating the health of the corridor pavement sections is to transform the measured data into a useable rating. This rating is the performance indicator (PI) first presented in section 3.5.1 of the thesis. After a PI is calculated it can be combined into a health indicator using Equation (20). To get the PI a series of transfer functions were developed for the data being collected.

A linear transfer function for each distress type was selected. In this case only two values of the PI as a function of measured distress are needed to define the function. The two points used were the upper and lower ranges for each distress. These are summarized in Table 19.

Table 19: Transfer Function Boundary Values

Performance Indicator	Data Type	Upper Bound		Lower Bound	
		Value	PI	Value	PI
IRI	in/mi	60	9	200	2
Rutting	in	0	10	0.5	2
Cracking	%	0	10	50	2

These ranges were selected based on the VDOT acceptable levels of distress. The bounds represent the typical values used to classify failure of a distress type. As with the scale, these values can be changed if a different set of ranges are desired.

The transfer functions used were assumed to be linearly declining values. The bounds were placed into a graph and fitted with a linear trend line to establish the transfer equation for each of the distresses. Figures 14, 15 and 16 display the graphs used in determining the transfer equations.

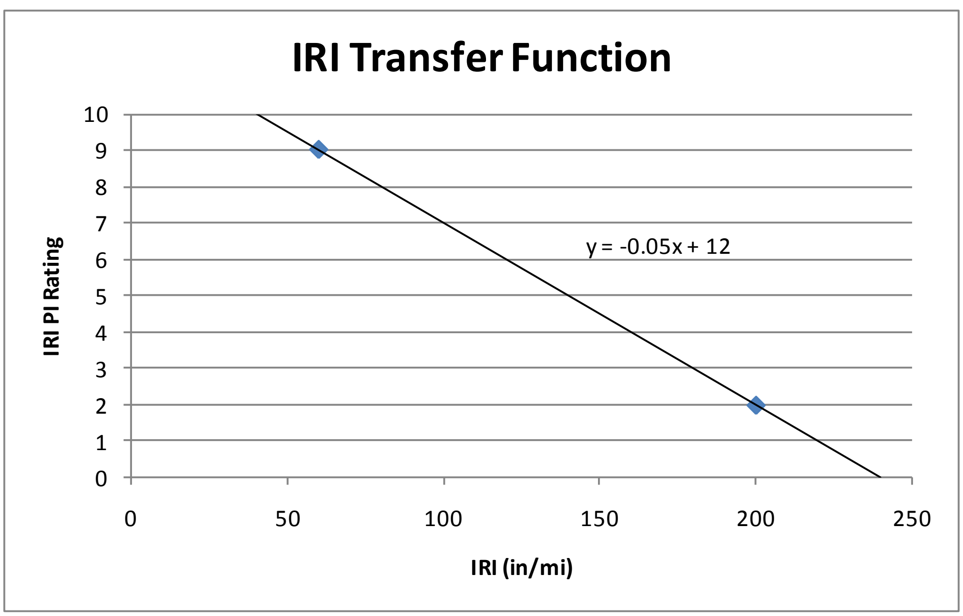

Figure 14: IRI Transfer Function Graph

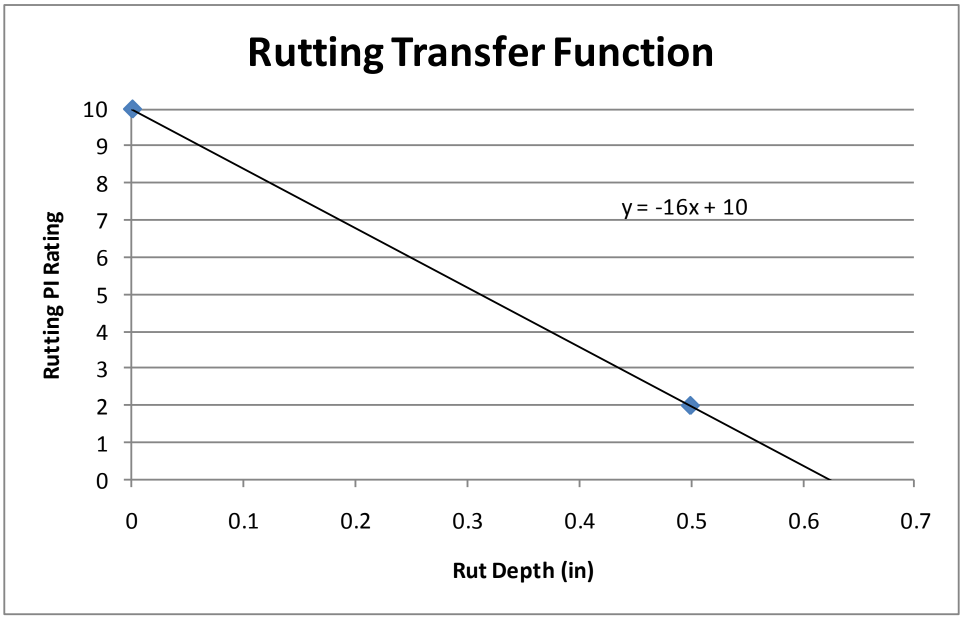

Figure 15: Rutting Transfer Function Graph

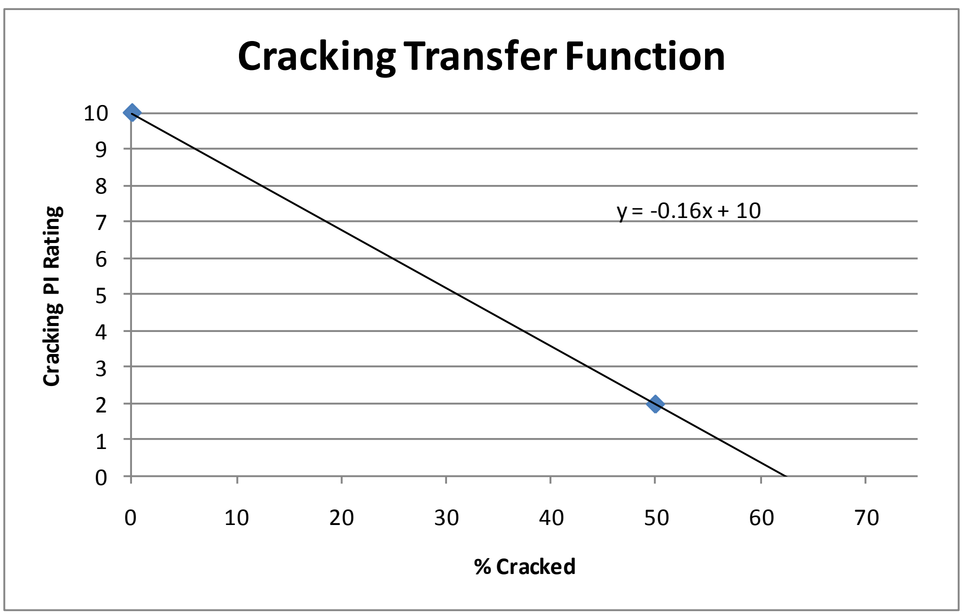

Figure 16: Cracking Transfer Function

These functions can also be set to decline in rating exponentially or any other functions if desired. To do so one or more intermediate bound would need to be set. The trend line would then be fit using an appropriate curve. For the purposes of this project a simple linear equation was used.

To limit values of PI between 0 and 10, the functions shown in Figures 14 through 16 had maximum and minimum limits set applied. The final transfer equations to calculate the performance indicators for each of the three distresses are shown in Equations (27), (28), and (29).

$$PI\_IRI = \min(10, \max(0, -0.05*IRI + 12)) \tag{27}$$

$$PI\_Rut = \min(10, \max(0, -16*RD + 10)) \tag{28}$$

$$PI\_Cr = \min(10, \max(0, -0.16*TP\_Crack + 10)) \tag{29}$$

Where,

IRI = International Roughness Index (in/mi)

RD = Rut Depth (inches)

TP_Crack = Total Area of Cracking (%)

These equations allow engineers to take measured field distresses and convert them into a rating for each individual distress. The cracking quality measure, TP_Crack is a combination of three different cracking measures described in more detail in the following section.

The advantage of using similar performance indicators for different distresses is that an engineer can compare different distresses using the same scale. These PI values can then be combined to obtain the health indicator rating.

Cracking Technical Parameter

This project considered three different types of cracking in the evaluation of pavement sections. These three cracking types were fatigue (or alligator), transverse, and longitudinal. To calculate the total percent cracking the values needed to be combined into a single percentage of the total area. The units of measure for each crack type are not the same. Alligator cracking is measured in square feet whereas longitudinal and transverse cracking are measured in linear feet.

Therefore two equations to convert measured cracking into percent total area cracked were developed. The first equation is used for cracks measured in square feet and is presented below as Equation (30):

$$TP\_A\_Crack = \min(100, \frac{1}{A_s} * \sum_n [W_n * \sum_i [S_i * A_i]] * 100) \quad (30)$$

Where,

TP_A_Crack = Total Cracked Area (%)

A_s = Area of Section (ft^2)

W_n = Weight of Crack Type

S_i = Severity of Crack Type

A_i = Area of Crack Type (ft^2)

The severity of the crack type can be assigned integer values from 1 to n with 1 being the least sever and n the most sever. The value of n can be independently set by each agency depending on how they classify crack severity. For example a low, medium and high classification would result in n=3. The crack severity's influence is to increase the total cracked area (Equation 30). Finally a 100% total cracked area is set as a maximum limit value. W_n is used in case more than one type of cracks is measured in units of square feet. In this thesis, only fatigue cracking is measured in square feet and W_n was set to 1.

The second equation is used for cracks measured in linear feet and is presented in Equation (31).

$$TP\_L\_Crack = \min(100, \frac{1}{A_s} * \sum_n [W_n * I_{crack} * \sum_i [S_i * A_i]] * 100) \quad (31)$$

Where,

TP_L_Crack = Total Cracked Area (%)

A_s = Area of Section (ft^2)

W_n = Weight of Crack Type

I_{crack} = Affected Width of Linear Crack (Value of 1 ft used)

S_i = Severity of Crack Type

A_i = Area of Crack Type (ft^2)

The main difference is the addition of the affected width of linear cracks parameter. This parameter represents the width of pavement along the crack that is affected by the presence of the crack to transforms the linear measure of the crack into an area measure. Wn was set to 0.78 for each of longitudinal and transverse cracks so that fatigue cracking had more weight to the calculation of the cracking PI.

To calculate TP_Crack the values of TP_A_Crack and TP_L_Crack are added together. If this value is more than 100% then a value of 100% is used as TP_Crack. Equation (29) can then be used to calculate the performance indicator for cracking in the section.

4.2.3. **Functional and Structural Health Indicators**

For the calculation of the PHR, only the functional (FHI) and structural (SHI) health indicators were considered. These performance areas had the most readily available quality measures that could be used in the combination. Table 1 demonstrated that these two areas were the most influential in the decision making process. For that reason, the FHI and SHI will be the only two health indicators used in the practical application of this methodology.

4.2.4. **Functional and Structural Health Indicator Weight Values**

To combine the PI values into the FHI and SHI weight factors to be used in Equation (20) needed to be set. The weights used ranged from 0.5 to 1.0 and are presented in Table 20.

Table 20: Weights used in Pavement FHI and SHI Calculations

PI Type	Functional Health (FHI)	Structural Health (SHI)
IRI	1.0	-
Rutting	0.5	0.7
Cracking	-	1.0

Each value was assigned based on the importance of the indicator. IRI was the most important PI in calculating FHI which is why the weight is a 1.0. For structural health the cracking was the more critical PI and received its weight of 1.0. Rutting was considered to be a similar PI in the structural health which is why the weight is closer to 1.0. For FHI it is given less weight because it has much less influence than IRI in the rating.

These weights have been assigned in order to demonstrate the methodology. If desired these values can be adjusted, as with most of the assigned values have been in this methodology.

4.2.5. **Overall Corridor Pavement Health Rating Weight Values**

The combination of FHI and SHI into a pavement health rating (PHR) is done using equation 23. The weights used for this combination are presented in table 21. For pavements the researchers determined that the functional health was slightly more significant than the structural health. User perception and ride quality are major decision factors when determining road projects. SHI was also very important which is why the rating is closer to 1.

Table 21: Weights used in Pavement Health Rating Calculation

Health Index Type	Weight Value
Functional	1.0
Structural	0.75

4.3. *Bridge Health Rating Methodology*

The basis for the calculation of bridge health is a combination of the CBHI and the NYSDOT Method for Evaluating Bridges. The method incorporates the element level inspection data and a calculation method similar to the CBHI. The selected individual quality measures are the condition of the various bridge elements, as shown in the inspection reports demonstrated in Table 2. However the method uses the element weights of the NYSDOT method. The following sections describe the basics of the method which are unique to bridges.

4.3.1. **Bridge Element Weights**

An important characteristic of the weights used by the CBHI is their dependence on a cost factor. Cost values depend on availability of material and labor, construction access, etc. These typically vary across the nation. If cost is incorporated into the methodology this will influence the calculated PIs and make it harder to compare the health of the highway system across the nation. For this purpose, a system of element weights based on the NYSDOT Bridge Rating method was adopted.

Eliminating cost from the individual bridge ratings helps in two ways. The first is that removing cost also removes the variation in cost across the United States. Depending on material type bridge cost can vary greatly due to availability of the material, availability of labor, construction access, etc. To update the cost of each element depending on location makes this project's bridge methodology impractical for use across the country. The second benefit is that another element weight besides failure cost can be assigned to each element consistently across the country. Having a single value for each element type will eliminate the variations in bridge ratings caused by varying failure costs. As shown in a paper by Kang and Adams (2010) the bridge health index is influenced more by actual bridge condition but failure cost can cause differences in lower rated bridges. This paper is described more in detail in section 2.4.2.2.

To achieve this goal of eliminating failure cost, a new system of element weights was adopted from the NYSDOT Bridge Rating method. For this method each element type, regardless of material, is assigned a weight based on the element's importance to the load path of the bridge. The original weights ranged from 1 to 10. However, these were modified to range from 0.1 to 1.0 with 0.1 being not important to 1.0 being very important. For this project, the elements included were typical elements such as primary members, abutments, decks, piers, joints, etc. Table 22 presents the element weights used for this project. The weights used in this project were selected based on the sample data provided to the research team by VDOT. The weights can be adjusted or have more elements added to the list if so desired.

Table 22: Bridge Methodology Element Weights

BRIDGE ELEMENT WEIGHTS	
Primary Members	1.0
Deck	0.8
Abutments	0.8
Pier Cap	0.8
Pier Columns	0.8
Bearings	0.6
Approach Slab	0.5
Walls	0.5
Joints	0.4

The advantage of these weights is that the values can be used no matter which state the bridge is located and is not dependant on the cost of an element at a location. Also when used in the CBHI method it does not need to be altered. The values are used in place of the failure cost with no adjustments to the CBHI Method. This is a big advantage when developing the bridge methodology to be used in this project.

4.3.2. **Element PI Calculation**

The calculation of the PI for each element is done by multiplying the quantity of each condition state by a condition state weight and dividing by the total quantity. The first step is to establish the condition state weight factors, as presented in equation (32).

$$WF_i = \left[1-\left(\text{Condition State \#-1}\right)\left(\frac{1}{\text{State Count-1}}\right)\right] \qquad (32)$$

Where,

WF_i = Element Weight Factor for Condition State "i"

Condition State # = Condition State "i"

State Count = Total Number of Condition States (Value of 5)

The next step is to calculate the Current Element Quantity (CEQ) and Total Element Quantity (TEQ) values. Equations (33) and (34) show the calculation of TEQ and CEQ respectively.

$$TEQ = \sum EQ_i \quad (33)$$

$$CEQ = \sum EQ_i * WF_i \quad (34)$$

Where,

TEQ = Total Element Quantity

CEQ = Current Element Quantity

EQ_i = Element Quantity in Condition State "i"

WF_i = Element Weight Factor for Condition State "i"

These values are used in the calculation of element PI. This calculation is presented in Equation (35).

$$PI_E = \left[\frac{CEQ}{TEQ}\right] * 10 \quad (35)$$

Where,

PI_E = Performance Indicator of Element "E"

CEQ = Current Element Quantity of Element "E"

TEQ = Total Element Quantity of Element "E"

4.3.3. **Functional and Structural Health Indicators**

As stated in Section 4.2.3 the FHI and SHI will be the only two health indicators used in the practical application. The weights used for the calculation of the health indicators are presented in Table 22. For the FHI calculation a weight of 0.8 was applied to the bridge deck. However since it was the only element included in the calculation the weight could be any value and still have the same final value. As more elements are added the weights will need to be adjusted.

4.3.4. **Overall Corridor Bridge Health Rating Weight Values**

The final step is to combine the FHI and SHI into an overall bridge health rating (BHR). This was done using Equation (22). The weights used to perform this calculation are presented in Table 23. These weights reflect how important each health indicator is to the overall BHR. The structural weight was chosen as the highest weight since this category contained more elements. The FHI only includes the quality of the deck so it was given the lower weight. The bridge deck was also included in the structural health indicator.

Table 23: Weights used in Bridge Health Rating Calculation

Health Index Type	Weight Value
Functional	0.3
Structural	1.0

4.4. *Customization Summary*

The customization of this method to the provided data shows how the asset PI values were calculated and combined to achieve an overall corridor health rating. The weights used in this section were selected by the researchers in an attempt to accurately describe critical elements and assets contained in a corridor network. The weights can be changed to reflect different perceived element or asset importance and the equations can be adjusted to include new elements or asset types. The method is very flexible and can be changed with minimal effort. The use of VDOT data provided the project with an opportunity to test if the method is comparable to current practice for individual assets. The results of this analysis are presented in chapter 5.

CHAPTER 5: **Practical Application Demonstration**

This chapter demonstrates how the methodology can be put into practice. The Virginia Department of Transportation (VDOT) has provided pavement and bridge data, which were used in the demonstration. Two sections of Interstate-81 were analyzed and a corridor health rating (CHR) was calculated for each section. In addition, the calculated ratings for pavements and bridges were compared to the current ratings used by VDOT. The pavement rating for each individual section within the corridor section was compared to the VDOT Critical Condition Index (CCI). The bridge rating for each structure was compared to the NBI rating. The most recently collected data for each asset were used.

5.1. ***Selection of Test Corridor***

The first step in the analysis process was to select two appropriate sections of IHS route to compare the ratings at different locations. The goal was to use two sections that were located on the same route but were separated by a large distance. The route chosen for this project was Interstate-81 (I-81). This route was chosen because it is a major route in the state of Virginia, has varying levels of traffic, and has readily available relevant data from VDOT.

Route I-81 is approximately 325 miles in length in the state of Virginia from the southern border with Tennessee to the northern border with West Virginia. For this demonstration, two 50 mile corridor sections were chosen; one between mile posts (MP) 50 and 100 and one between MP 250 and 300. These sections were selected because they are separated by 150 miles and are sections which intersect with two other IHS Routes. MP 50 to 100 connects with I-77 and MP 250 to 300 connects with I-66. I-66 is known for having a higher number of vehicles than I-77 since it is the major connector to Washington, D.C. and to the Virginia Inland Port. Therefore it was hoped that the difference in traffic would affect the condition of each corridor section. Section 1, MP 50 to 100, contains a total of 65 bridges and Section 2, MP 250 to 300, contains 55 bridges.

Although sections of 50 miles in length were used for this project, the sections could have been selected to span between major intersections with other IHS routes into I-81 or between major cities. For example one section would be between the intersection of I-64 and I-81 and the intersection of I-66 and I-81 or I-95 between New York and Washington, D.C.

5.2. ***Pavement Health Rating Methodology Results***

All data provided for this demonstration was collected using the automated ARAN system. The data collection was done by a consultant for the Asset Management Division of VDOT. This system collected several data items in approximate 0.1 mile sections, continuously along the entire route. Data provided includes IRI, rutting, and individual cracking values needed to calculate the PI ratings. The calculated PHR for the smaller sections were then compared with the CCI values also calculated using the ARAN system. The following sections present the results of the effect of the PHR by PI, FHI, and SHI values, comparison of PHR to the provided CCI, and the final PHR for northbound and southbound for each test section. Excel spreadsheets were used to calculate all values.

5.2.1. **Performance Indicator Influence on Functional and Structural Health**

For each smaller section contained in the corridor the values of PI_IRI, PI_Rut, and PI_Cr were calculated using Equations (27), (28), and (29). These were then used to calculate the FHI and SHI. The FHI and SHI values were used in the next step to calculate the section PHR for individual pavement sections. Equation (20), with the weights presented in Table 20, was used for this purpose. The FHI was calculated using PI_IRI and PI_Rut. The SHI was calculated using PI_Rut and PI_Cr.

The results of these calculations are presented in Figures 17 through 20. These graphs show the values of PI along the length of each section in both the north and south directions. Also shown in these figures are the plot of PHR values, or SR, and the CCI ratings.

5.2.2. **Influence of Functional and Structural Health on Individual Section Ratings**

The next phase of the project was to use the FHI and SHI values in Equation (21) to calculate the individual SR for each small pavement section within the corridor section. The weights used for this calculation were presented in Table 21. For the pavements more weight was placed on the FHI and slightly less was placed on the SHI of the section. The results are also presented in Figures 17 through 20.

The graphs show which PIs have more effect on SHI and FHI. As expected the FHI trend follows mostly that of PI_IRI, the indicator given the highest weight. Rutting also has an effect on the FHI because in sections of low PI_Rut the FHI drops to match this low indicator. For SHI the trend mostly follows that of PI_Cr however PI_Rut also has a significant effect on SHI evem more than it does on FHI. This is due to the higher weight given to PI_Rut in the SHI calculation.

Also demonstrated from the graphs is the influence of FHI and SHI on the individual section ratings. As expected the SR values mostly follow the FHI trend, which has the higher weight. However some sections were more influenced by very low SHI ratings, demonstrating the methods ability to capture the lower structural health sections.

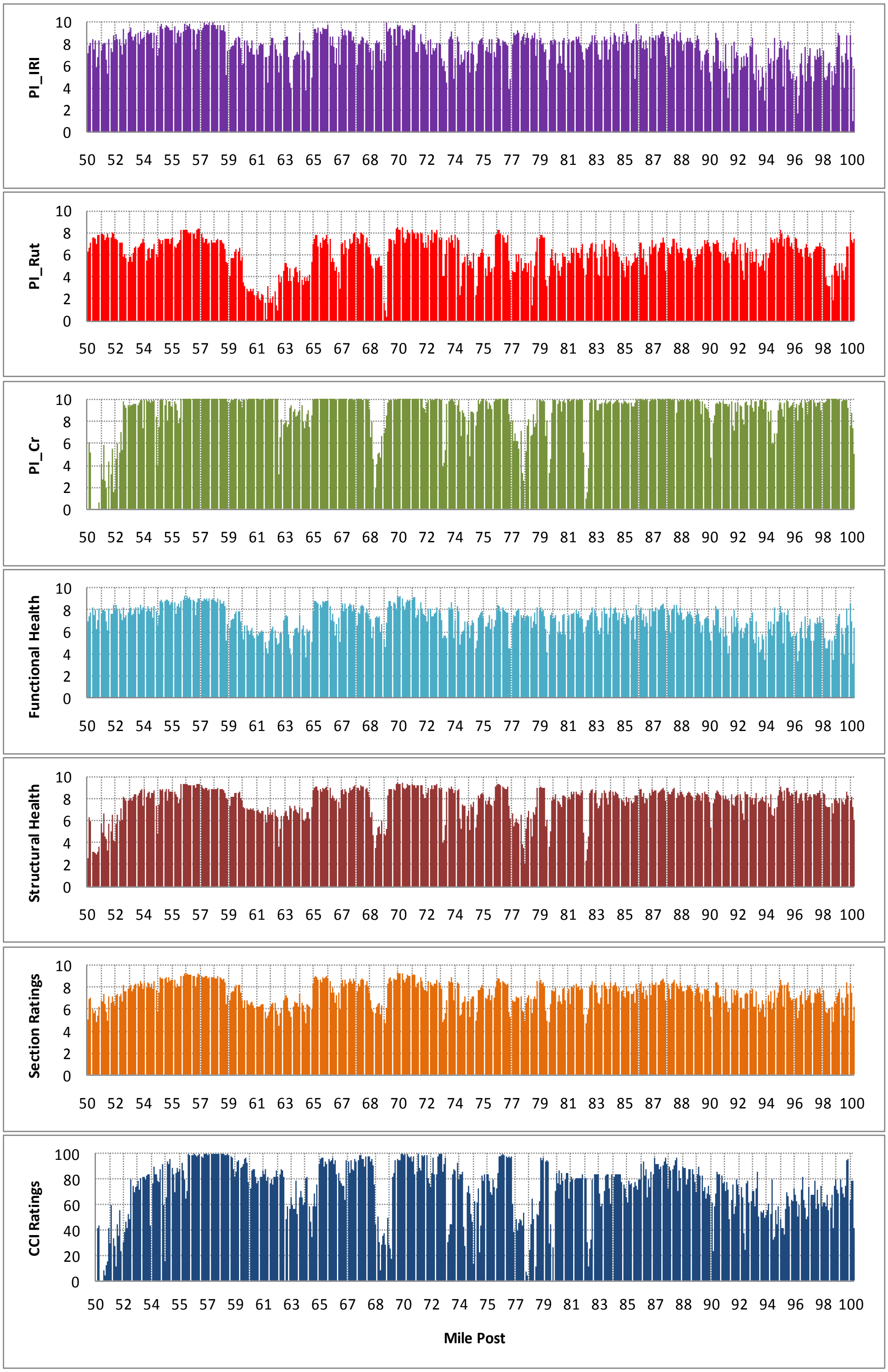

Figure 17: Comparison of PI, FHI, SHI, SR, and CCI Values MP 50-100 Northbound

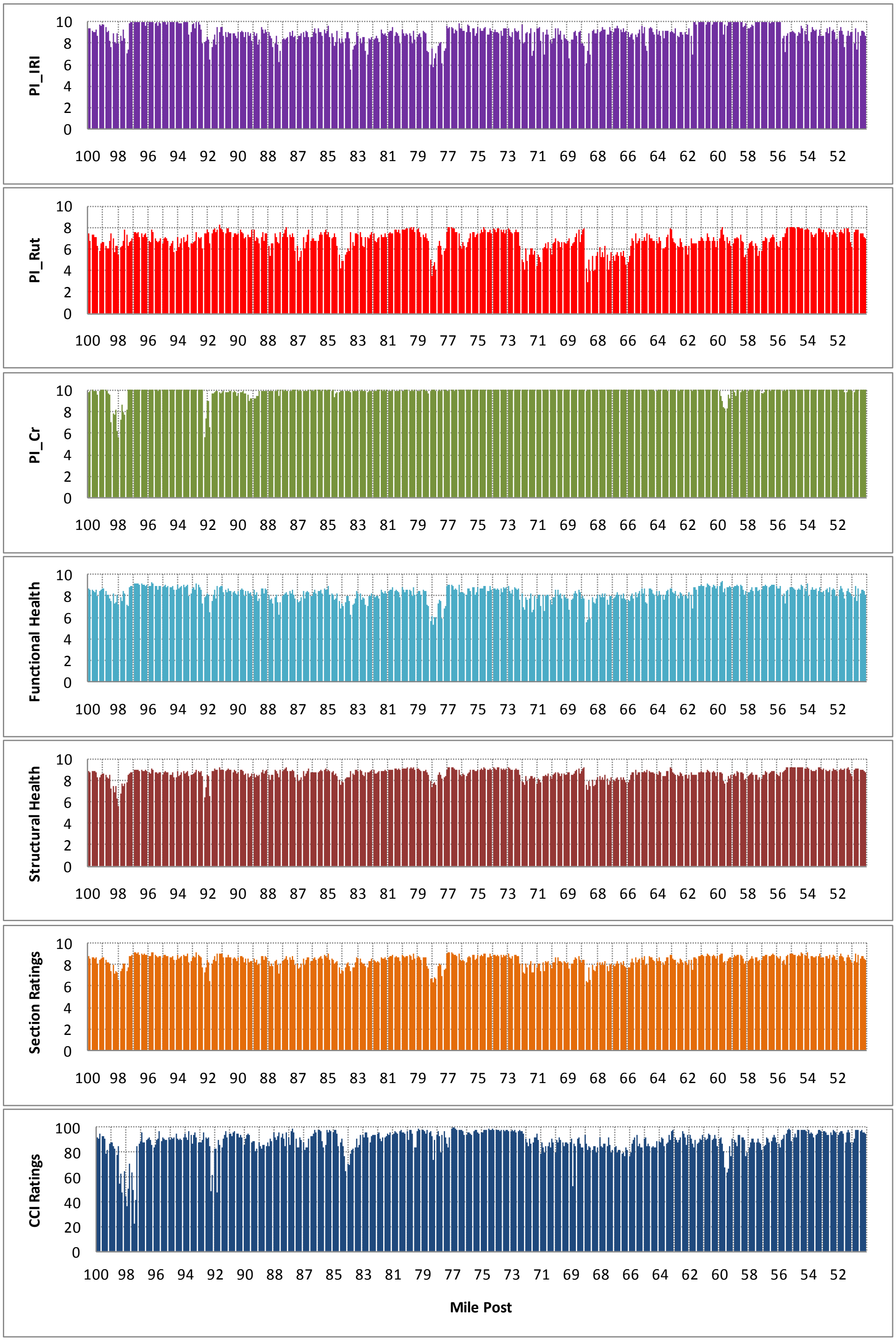

Figure 18: Comparison of PI, FHI, SHI, SR, and CCI Values MP 50-100 Southbound

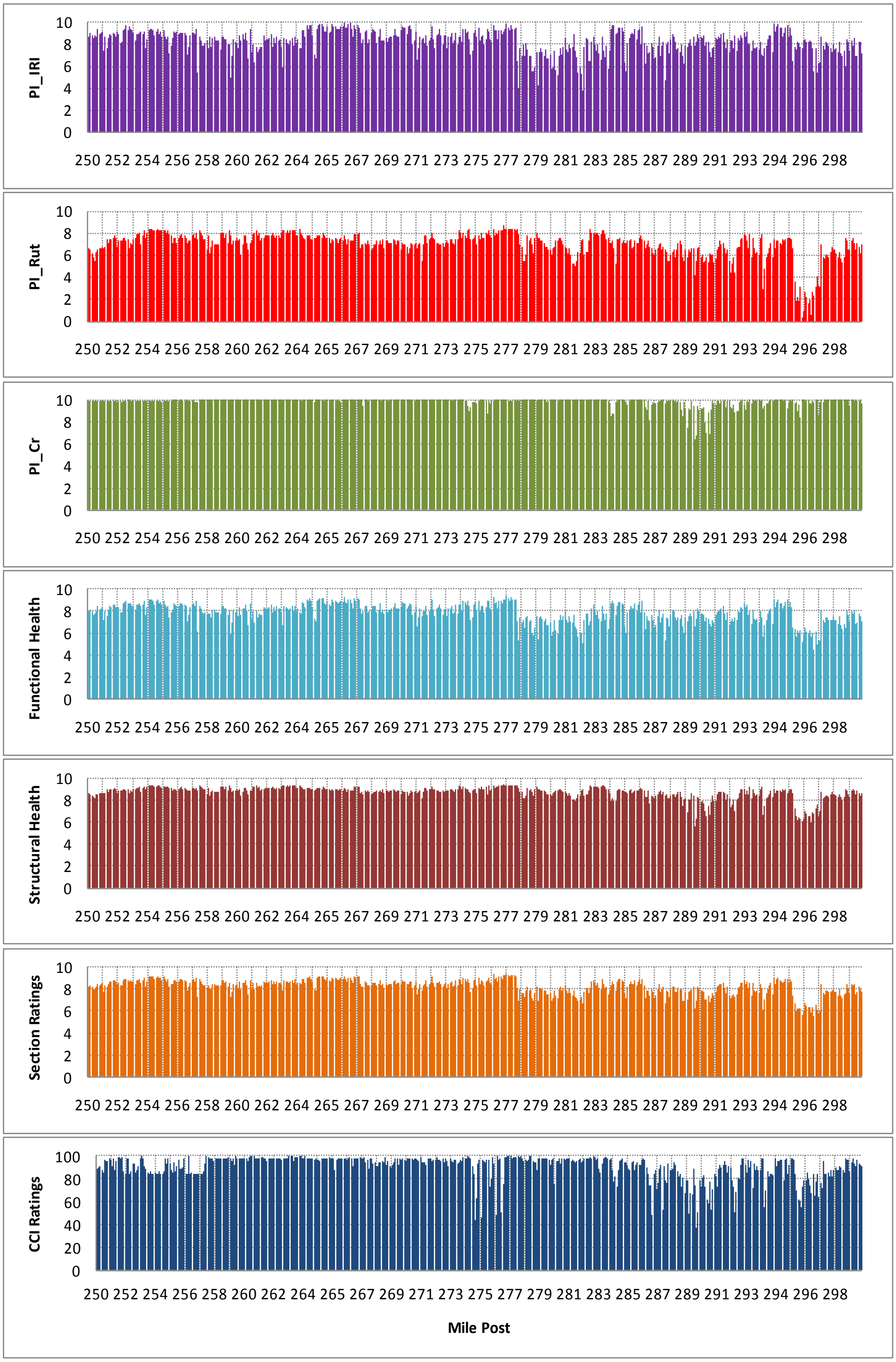

Figure 19: Comparison of PI, FHI, SHI, SR, and CCI Values MP 250-300 Northbound

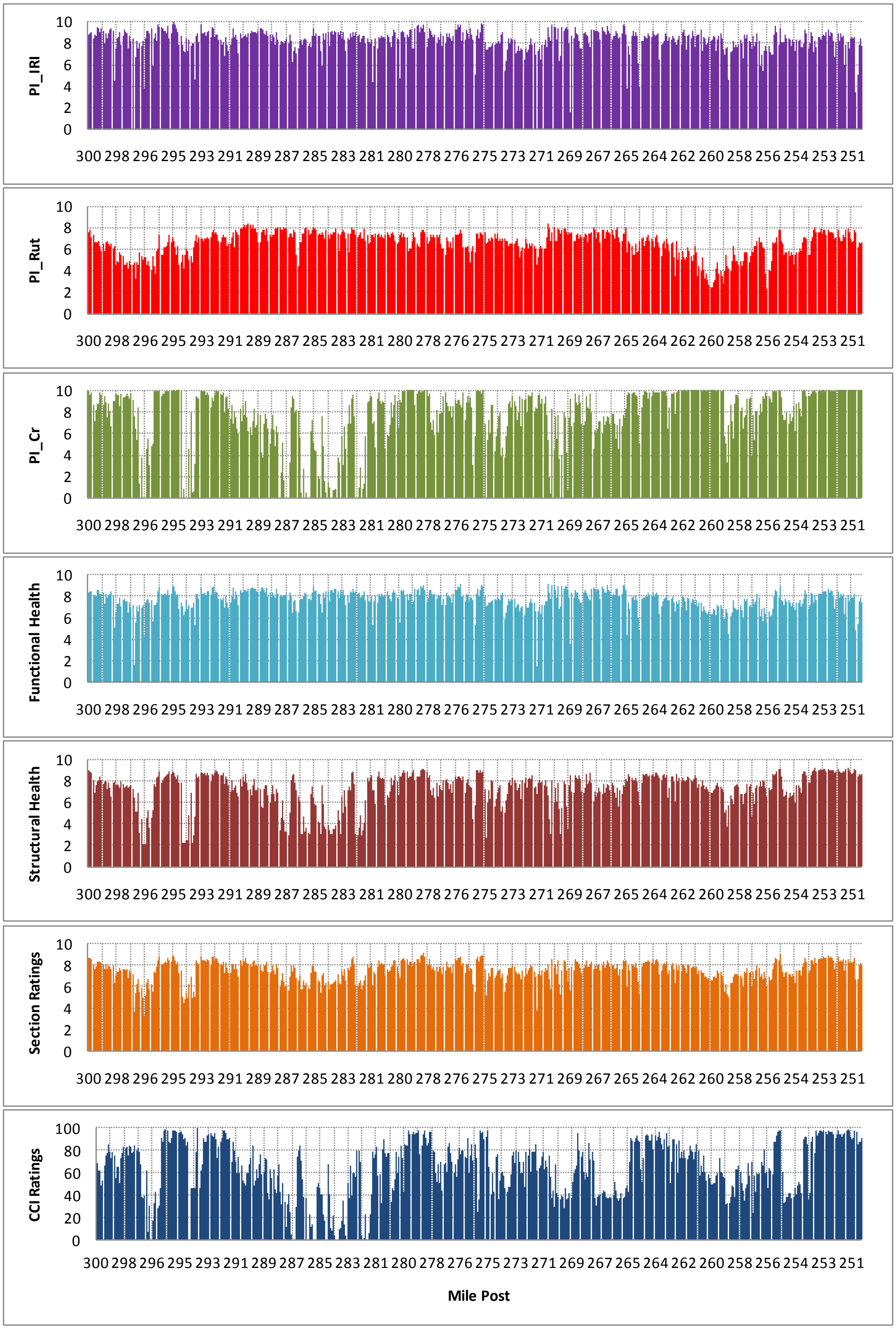

Figure 20: Comparison of PI, FHI, SHI, SR, and CCI Values MP 250-300 Southbound

5.2.3. **Comparison of Pavement Section Ratings to VDOT CCI Ratings**

To verify that the proposed method produces values comparable to the current condition determined by VDOT, the SR values were plotted against the CCI values in Figures 21, 23, 25, and 27. The plots of SR and CCI are not expected to follow the exact trend for three reasons. The first reason is the difference in scale. The second reason is the distresses included in the calculation of the condition are not the same. The proposed method only uses three distresses which reflect data being collected frequently at the national level. The VDOT CCI rating uses 9 types of distresses not including IRI. The third reason is the CCI divides the 9 distresses into two categories, load and non-load related, and creates a rating for each. The minimum of these two values is reported as the CCI. Therefore in high areas of only load or non-load related distresses, the rating of the section could drop to 0 if even if the other category is in decent condition.

These reasons have made a direct comparison between the two ratings difficult; however the results have shown that the two rating methods do follow a similar trend. Areas with a CCI of 0 are the major differences between the two graphs.

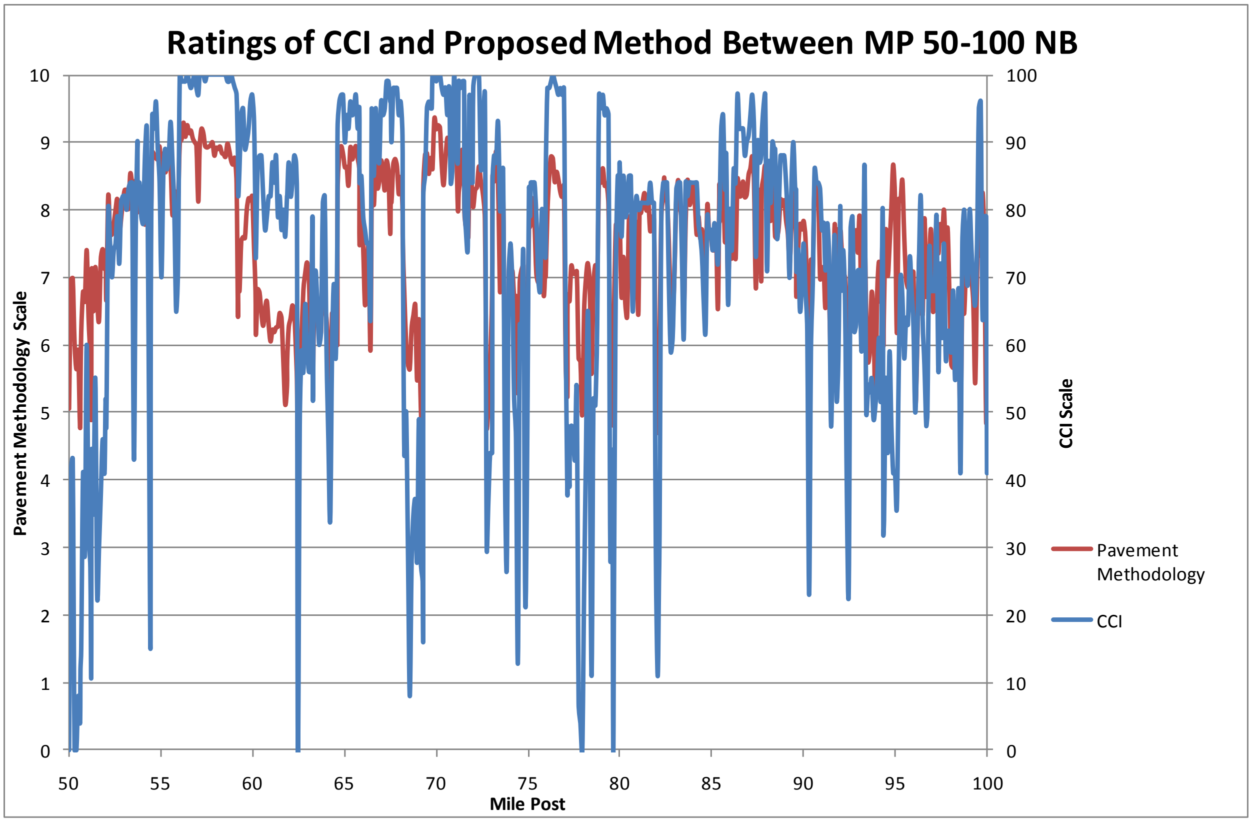

Figure 21: Graph of CCI and SR along Corridor Section MP 50-100 Northbound

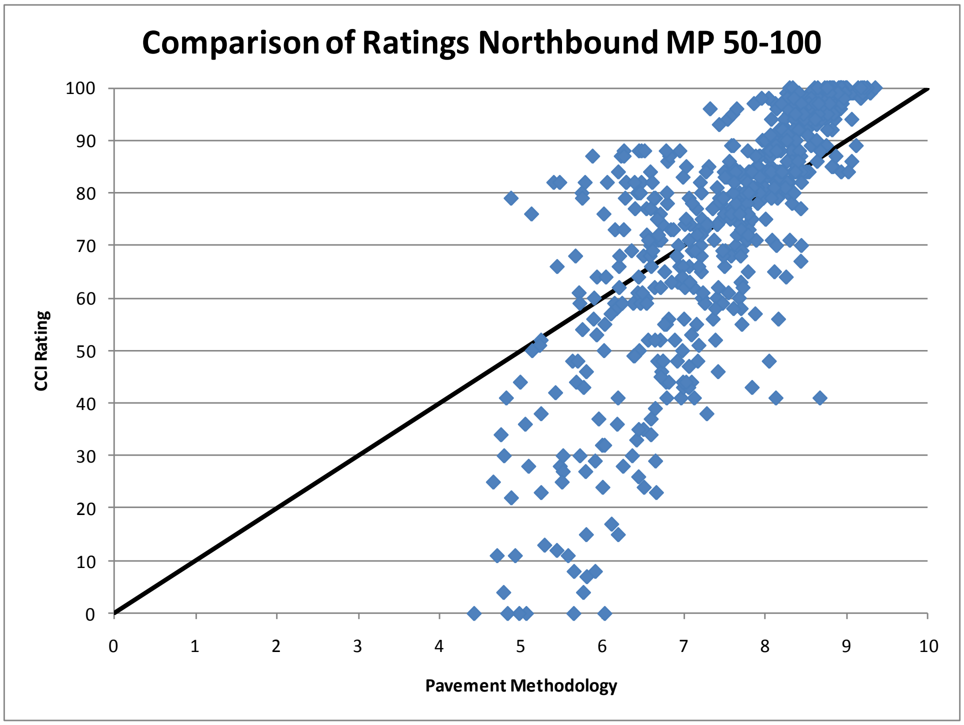

Figure 22: Comparison of CCI vs. SR for Individual Sections in MP 50-100 Northbound

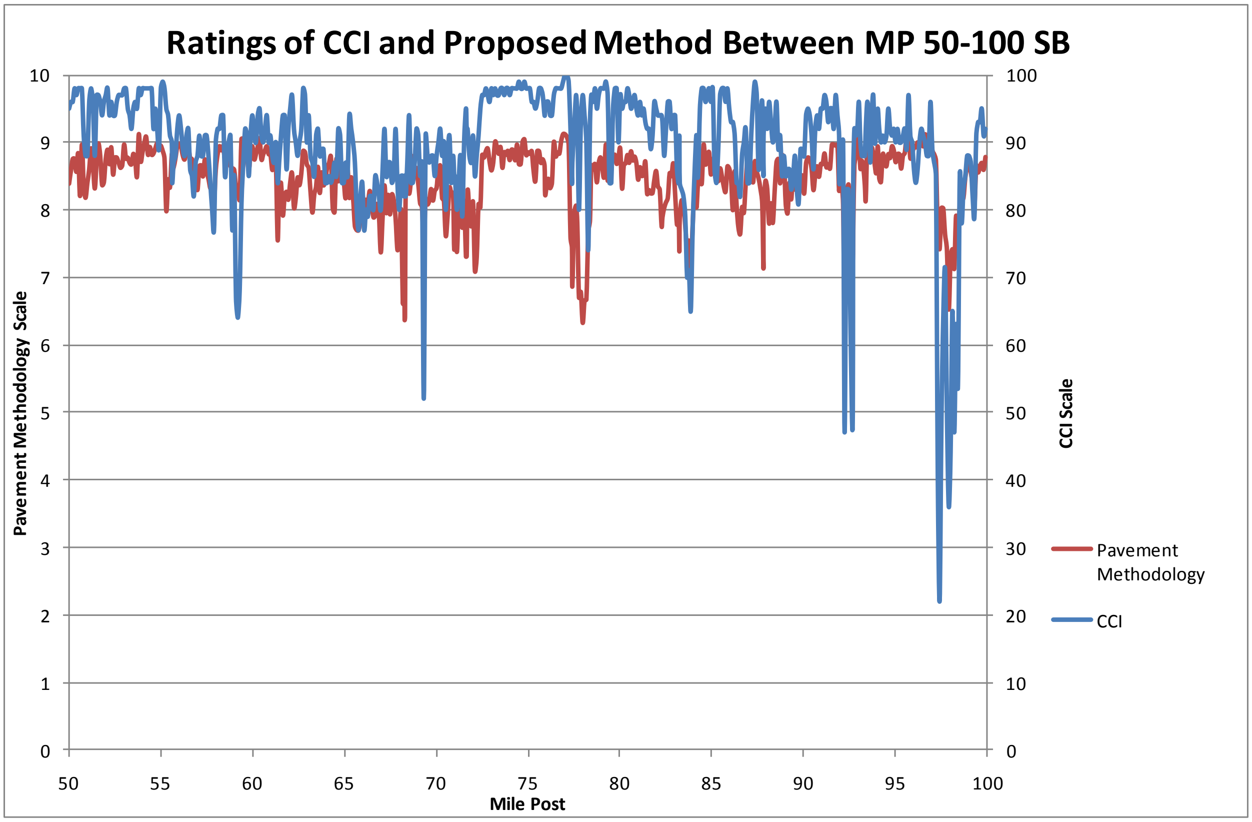

Figure 23: Graph of CCI and SR along Corridor Section MP 50-100 Southbound

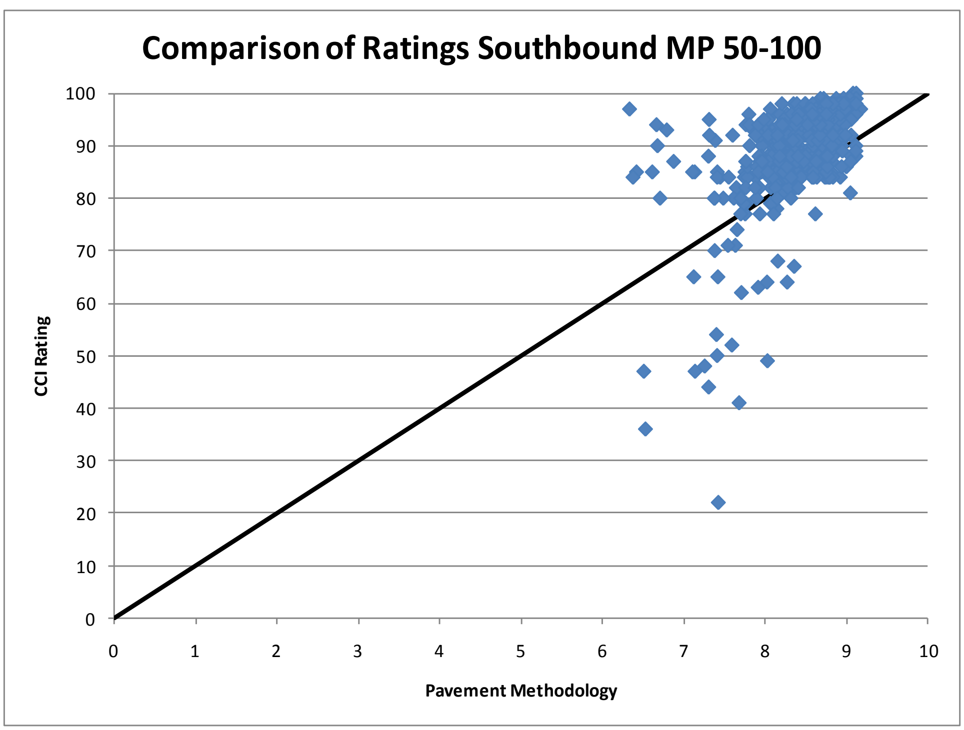

Figure 24: Comparison of CCI vs. SR for Individual Sections in MP 50-100 Southbound

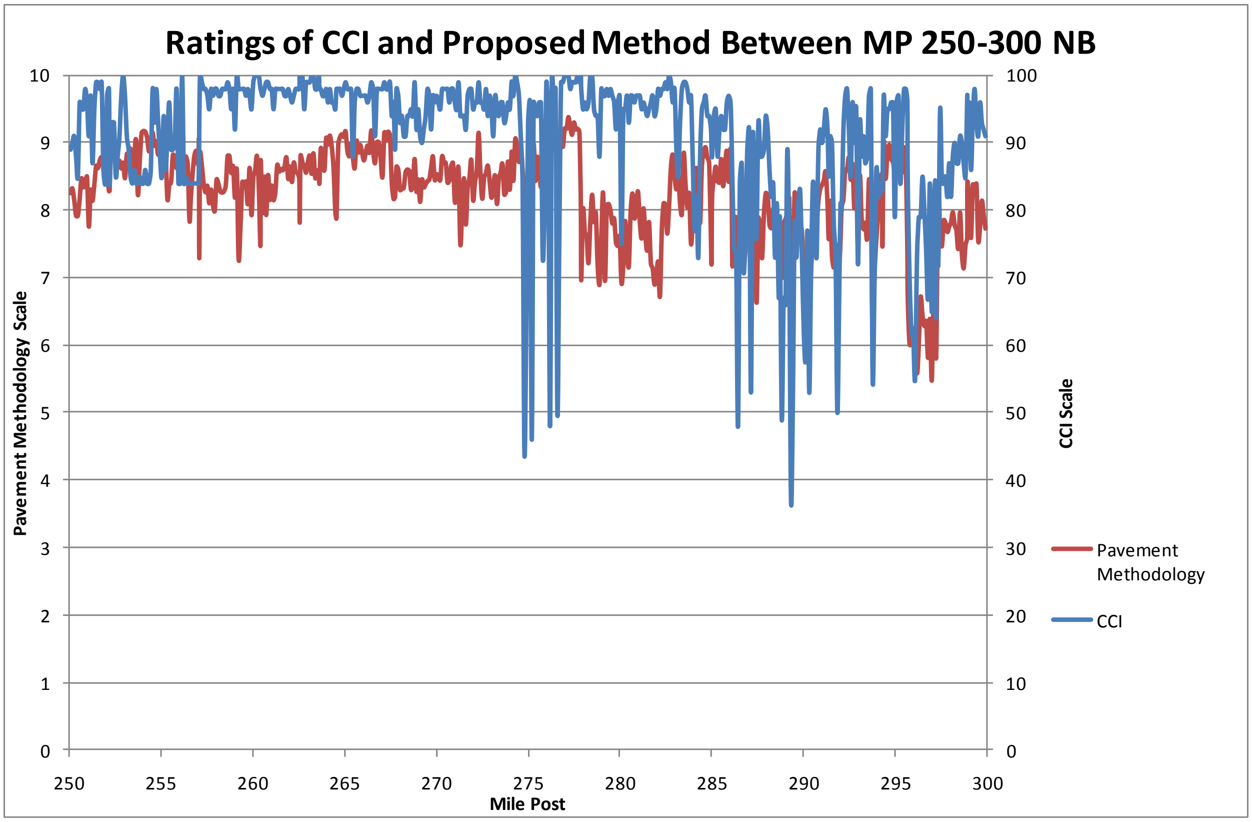

Figure 25: Graph of CCI and SR along Corridor Section MP 250-300 Northbound

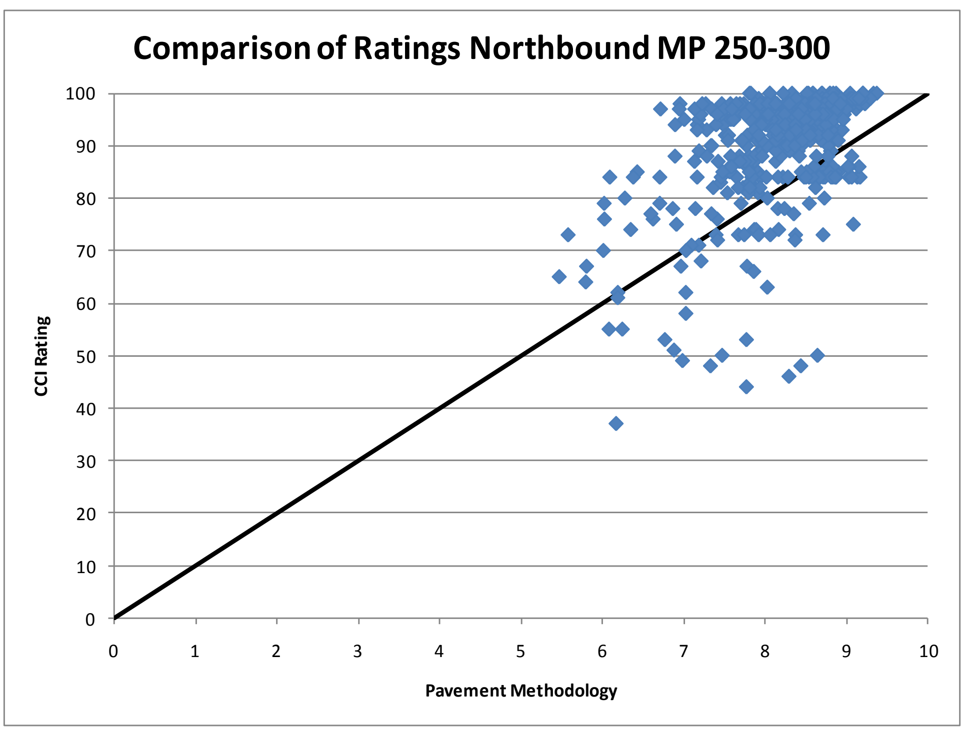

Figure 26: Comparison of CCI vs. SR for Individual Sections in MP 250-300 Northbound

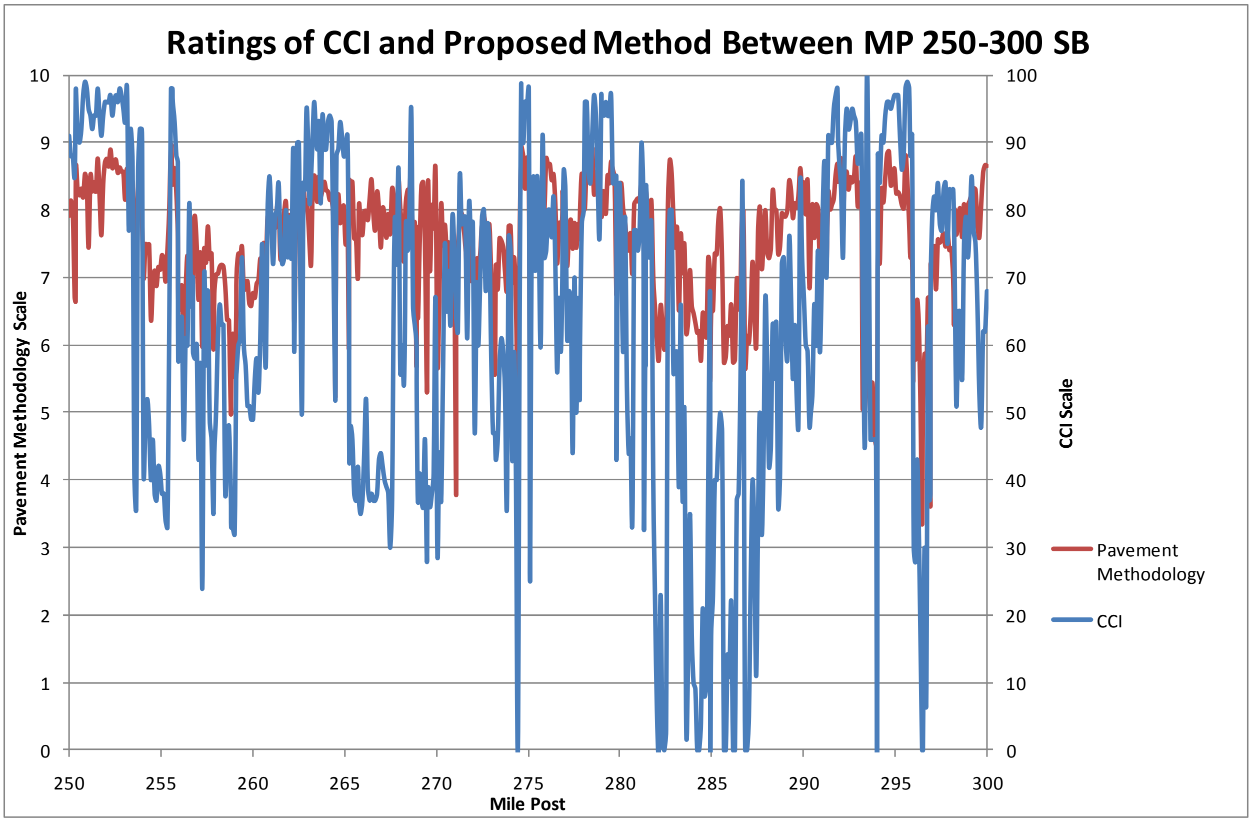

Figure 27: Graph of CCI and SR along Corridor Section MP 250-300 Southbound

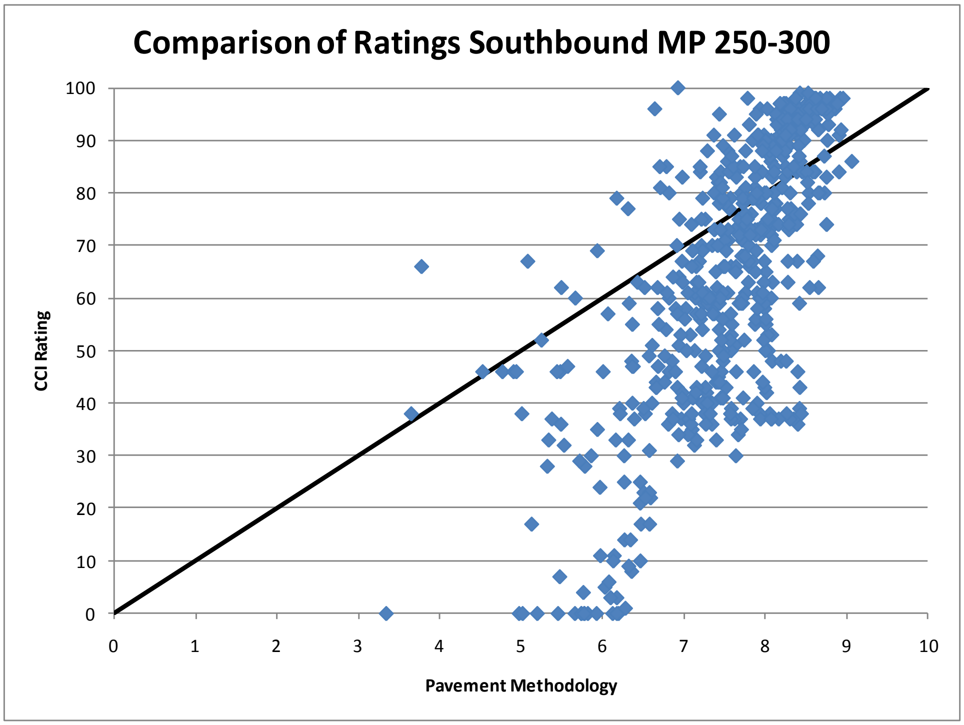

Figure 28: Comparison of CCI vs. SR for Individual Sections in MP 250-300 Southbound

In general, the SR for individual sections is higher than the CCI. This was expected as the CCI is the minimum of functional and structural measures whereas the SR is a weighted average. With the proposed method, a rating of 0 would require all three PI values to be zero. This would mean that the pavement has a failing IRI, rutting of 0.5 inches, and over 50% cracking in the section. This is highly unlikely to occur. With the CCI, the use of deduct values can make the controlling group of distresses go to zero more frequently.

Despite these differences the SR values and CCI values do follow a similar trend. The ratings are comparable to each other at most locations along all the sections. The correlation is not exact yet it is close enough to prove the validity of the proposed method ratings. To improve the correlation between ratings as shown in figures 22, 24, 26, and 28 there are two things that can be adjusted.

1. Adjusting the weights that combine the FHI, SHI, and SR values. Adjusting these weights can change the influence of individual PI values on the ratings. Changing these weights did not produce significant changes to the ratings calculated.
2. Change the transfer functions for the pavement distresses from linear deterioration models to exponential or parabolic models. For this project the transfer functions were developed assuming straight line deterioration. If the proposed method were implemented the transfer functions would need to be developed to match agencies' goals.

5.2.4. **Corridor Section Pavement Rating Calculation**

The final step in the (PHR) calculation for the corridor section is to combine the individual SR values. This was done for each direction in each section which resulted in 4 different ratings. To calculate the PHR a weighted average of the SRs was calculated according to Equation (22) which takes into account the length of the individual sections. The results were compared with a normal average of the individual SR values. Table 24 presents the results of the weighted average and the normal average for each section.

Table 24: Comparison of Pavement Health Rating Combination Techniques

SECTION	Weighted Average Rating	Pure Average Rating
Northbound MP 50-100	7.51	7.46
Southbound MP 50-100	8.45	8.43
Northbound MP 250-300	8.23	8.22
Southbound MP 250-300	7.58	7.52

The two values were very close because the lengths of the sections were approximately the same. The reason the weighted average method was used is due to its ability to capture the effects of a small test section. The standard section size was 0.1 miles was measured by the ARAN system, but smaller sections were calculated at event markers along the route. These could be county lines, district boundaries, etc. These small sections, sometimes 0.02 miles in length, have less weight to the final rating of the corridor PHR. Therefore the weighted average method should be preferred.

There is also a difference in the PHR based on the direction of travel within the section. MP 50-100 had an entire point difference between northbound and southbound directions. This difference could result from differences in the traffic, soil conditions, drainage of the pavement, etc. These results show that differences can exist between the travel directions within the same section.

To calculate the overall PHR for both directions the ratings for each direction for a corridor section were averaged together. Since the sections are approximately the same length, a pure average could be used. The final results are presented in Table 25.

Table 25: Final PHR Values for Corridor Sections

SECTION	CORRIDOR PAVEMENT HEALTH RATING (PHR)
MP 50-100	7.98
MP 250-300	7.91

The results show that the pavement health in the two sections is similar. The initial assumption that the higher traffic of I-66 might reduce the condition of the pavement was not confirmed. One possible reason for this is that the two sections are maintained to the same level of service, irrespective to deterioration rates.

The pavement health rating methodology proposed in this thesis provides several advantages. The plot of the individual PI values against the functional health, structural health, and section ratings can provide an indication about which distresses are the primary cause of lower SR values along the route. This can help target roads for project level improvements. It also allows engineers to select projects for maintenance based on their functional and structural performance. The method also provides a way of comparing overall pavement section ratings for different sections along the IHS. This can be expanded to include parallel routes and help target corridors which need more repairs on the network level. The method is a potentially great tool to report condition to FHWA, government officials, and the public in a straight forward single rating.

5.3. *Bridge Health Rating Methodology Results*

The data used to test the proposed bridge rating methodology was collected by various bridge inspectors who work for or are contracted by VDOT. The data was provided for use by VDOT Structure and Bridge Division. VDOT uses element-level inspection data along with the Pontis BMS system to identify which bridges are eligible for MR&R action. The data is a detailed report of individual bridge elements and what quantity is in each of five condition states. Condition state 1 is a “like new” condition and condition state 5 is “failed”. The entire structure is divided into its respective element type and condition state. VDOT provided element-level inspection reports from the last decade for bridges and culverts located within the sections of interest. Only bridges were considered in the analysis. Table 26 provides a sample of an inspection report for a typical bridge.

Table 26: Sample Inspection Report Bridge MP 50-100 Date 9/1/2007

CONDITION STATES					Element ID Key	Element Description	Quantity Units
1	2	3	4	5			
0	0	573.583	0	0	22	P Conc Deck/Rigid Ov	$feet^2$
0	0	304.678	6.21792	0	107	Paint Stl Opn Girder	feet
0	130	10	0	0	205	R/Conc Column	feet
1.2192	0.3048	0.3048	0	0	215	R/Conc Abutment	each
30.48	4.2672	0	0	0	234	R/Conc Cap	feet
0	42.3672	11.2776	0	0	301	Pourable Joint Seal	feet
0	18	0	0	0	311	Moveable Bearing	each
0	18	0	0	0	313	Fixed Bearing	each
2	0	0	0	0	321	R/Conc Approach Slab	each

Inspection reports were provided for a total of 65 bridges between MP 50-100 and 55 bridges between MP 250-300. Sizes of bridges, based on deck area, ranged from 303 ft^2 to 1858 ft^2 for both sections. The average size of bridge deck area for both sections is approximately 800 ft^2.

5.3.1. **Bridge Element Weight Factors for Use in Bridge Methodology**

The element descriptions provided in the inspection reports were broken down into general categories. This was done to help in assigning element weights for use in the bridge methodology. Different bridges use different types of materials for certain elements which made grouping of element descriptions in element type groups a necessity. For example, girder types found in the inspection reports included painted steel, unpainted steel, reinforced concrete, and prestressed concrete. All of these girder types were classified as “Primary Members” and were assigned an element weight of 1.0.

The general categories used for classification of elements and element weights were outlined in Table 22. After the elements were classified an Excel macro was used to automatically assign the element weights based on an Element ID Key.

5.3.2. **Calculation of Current and Total Element Quantities**

The next step in the process is to calculate the Current Element Quantity (CEQ) and Total Element Quantity (TEQ) for each element on a bridge. This calculation was done using Equations (33) and (34). The values from the sample bridge in Table 26 are shown in Table 27.

Table 27: Sample Bridge MP 50-100 CEQ and TEQ Values

Element Description	Element CEQ	Element TEQ
P Conc Deck/Rigid Ov	286.79	573.58
Paint Stl Opn Girder	153.89	310.90
R/Conc Column	102.50	140.00
R/Conc Abutment	1.60	1.83
R/Conc Cap	33.68	34.75
Pourable Joint Seal	37.41	53.64
Moveable Bearing	13.50	18.00
Fixed Bearing	13.50	18.00
R/Conc Approach Slab	2.00	2.00

The values of CEQ represent the quantity of the element which remains in usable condition. Quantities in Condition State 1 are included in the final CEQ and those in Condition State 5 have no effect on CEQ. The condition states 2, 3, and 4 have weighted values as calculated by Equation (32). The TEQ value is the total quantity of the element. From these values the PI of each element can be calculated.

5.3.3. **Calculation of Element Performance Indicators**

Using the CEQ and TEQ values the PI for each element is calculated using Equation (35). The equation takes the ratio of CEQ to TEQ to obtain a percentage of the total quantity that is still considered in usable condition. This percentage is then adjusted by a factor of 10 to calculate a PI on the rating scale used in this thesis. The resulting PI values are then used in the calculation of the FHI and SHI for the bridge. Table 28 presents the calculated of PI, CEQ, and TEQ values for the sample bridge presented in Table 26.

Table 28: Sample Bridge MP 50-100 Element PI Calculations

Element Description	Element CEQ	Element TEQ	Element PI
P Conc Deck/Rigid Ov	286.79	573.58	5.00
Paint Stl Opn Girder	153.89	310.90	4.95
R/Conc Column	102.50	140.00	7.32
R/Conc Abutment	1.60	1.83	8.75
R/Conc Cap	33.68	34.75	9.69
Pourable Joint Seal	37.41	53.64	6.97
Moveable Bearing	13.50	18.00	7.50
Fixed Bearing	13.50	18.00	7.50
R/Conc Approach Slab	2.00	2.00	10.00

These values can be used to identify elements which have low remaining quality or service life. As shown in the table, the major structural elements of the concrete deck and steel girders have low PI values. These elements appear in the highest quantity which makes them critical to the overall structure. Identifying which elements need MR&R action can help engineers in designing their maintenance or rehabilitation plan for the structure.

5.3.4. **Calculation of Functional and Structural Health Indicators**

The calculation of the FHI and SHI of the structure is the next step in the calculation of the overall corridor bridge health. For the demonstration, the FHI is assumed to be represented solely by the PI of the deck. The deck affects the ride quality of the bridge and was the only element considered for FHI. All elements were used in the calculation of SHI.

The calculation of these values was performed using Equation (20). The weights used were presented in Table 22. The results are presented in Tables 29 and 30.

As expected, the value of FHI is equal to the PI of the bridge deck. When only one element is included, multiplying and dividing by the weight produces the same value. The sample bridge had a FHI that was lower than the SH. Identifying which area needs more attention can be of great help to engineers when trying to choose projects. Using current data, the SHI will dominate decision making since the inspections are focused to structural assessment. Using the framework may lead to the inclusion of more functional measures in the condition rating of bridges.

Table 29: Sample Bridge MP 50-100 FHI and SHI Element Calculation

Element Description	Element PI	Element Weight	PI * Weight	
			Functional	Structural
P Conc Deck/Rigid Ov	5.00	0.80	4.00	4.00
Paint Stl Opn Girder	4.95	1.00	-	4.95
R/Conc Column	7.32	0.80	-	5.86
R/Conc Abutment	8.75	0.80	-	7.00
R/Conc Cap	9.69	0.80	-	7.75
Pourable Joint Seal	6.97	0.40	-	2.79
Moveable Bearing	7.50	0.60	-	4.50
Fixed Bearing	7.50	0.60	-	4.50
R/Conc Approach Slab	10.00	0.50	-	5.00

Table 30: Sample Bridge MP 50-100 FHI and SHI Final Calculation

	∑(PI*Weight)	∑(Weight)	Final Health Rating
Functional	4.00	0.80	5.0
Structural	46.35	6.30	7.4

5.3.5. **Calculation of Individual Bridge Ratings**

The next step is to use the FHI and SHI values to calculate the BHR of each bridge. This process is performed using Equation (21) and the weights presented in Table 23. More weight was assigned to the SHI since it incorporates the ratings of all the elements. The final bridge rating for the sample bridge is shown in Table 31.

The final rating is close to the SHI value, as expected. The weight used for the FHI can change as more data can be collected to represent the bridge's function. These could include deck IRI, joint faulting, friction, etc. Future work will be needed to include these in the proposed methodology.

Table 31: Sample Bridge MP 50-100 Bridge Health Rating Results

	Rating	Weight
Functional Health	5.0	0.3
Structural Health	7.4	1.0
BRIDGE RATING	**7**	

5.3.6. **Comparison of Bridge Methodology Ratings to NBI Ratings**

The comparison between the proposed rating methodology and the NBI rating was done to see if the ratings were similar. The objective was to see if the proposed methodology was comparable to the current rating system used at by FHWA. Bridges are currently rated at the federal level which is why the NBI ratings were used as a basis for comparison. In addition, since the proposed method was developed for national use it seemed fitting that the current system be used as baseline values for the comparison. Figures 29 through 32 present the ratings of both methodologies. Figures 29 and 31 present the distribution of the two rating methods. The other figures present a plot of NBI versus the BHR method developed for the project. The graphs are for both corridor sections; MP 50-100 and MP 250-300.

The results show that the distribution of NBI ratings is not very sensitive. The most common rating is a 5, which occurred 71 times within all 120 bridges in the two sections. This means that over 59% of the bridges have this rating. The highest occurrence of BHR values was a rating of 8 for 41 of the bridges. The proposed method showed more of a uniform distribution of ratings which were spread between 6 and 10. Those for the NBI between 4 and 7 except for two bridges rated an 8.

The lack of variation in NBI ratings results in a lack of distinction between bridges in dissimilar condition. Using figures 30 and 32 it is clear that the bridges rated with a NBI of 5 had ratings that varied between 6 and 10 for BR values. These figures also show that the BR ratings are slightly higher than the NBI ratings.

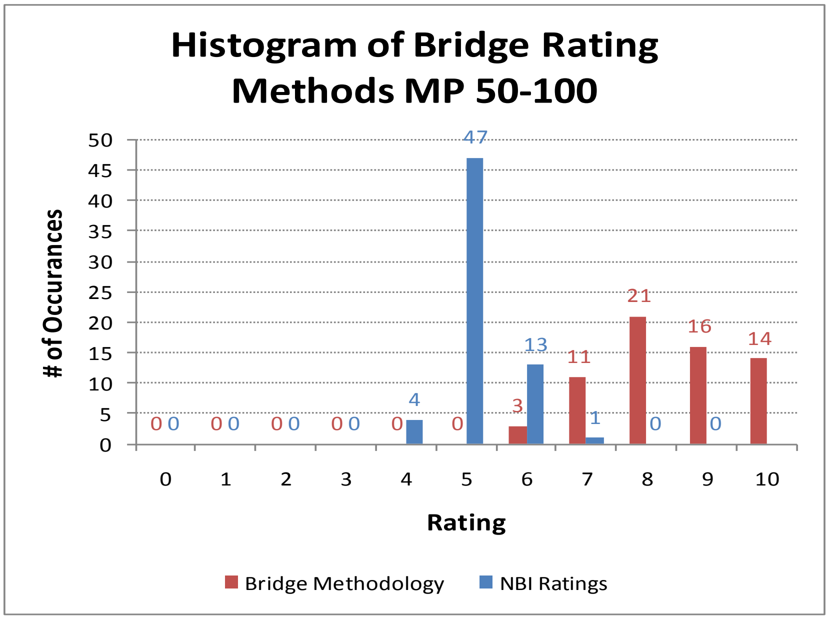

Figure 29: Histogram of NBI and Bridge Methodology Ratings MP 50-100

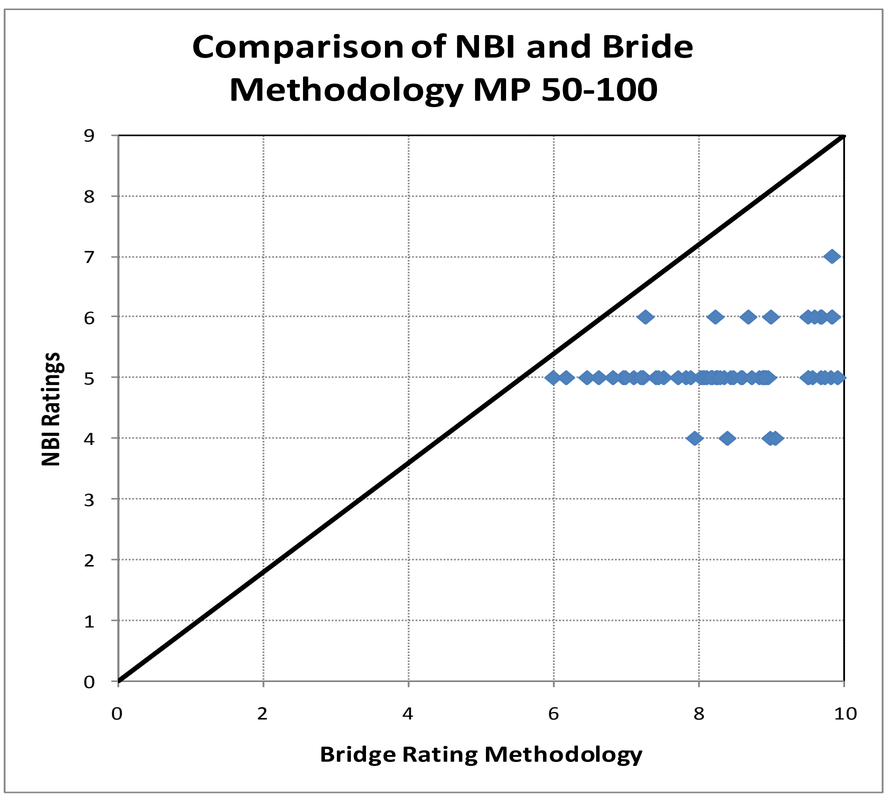

Figure 30: Comparison of NBI and Bridge Methodology on Individual Bridges MP 50-100

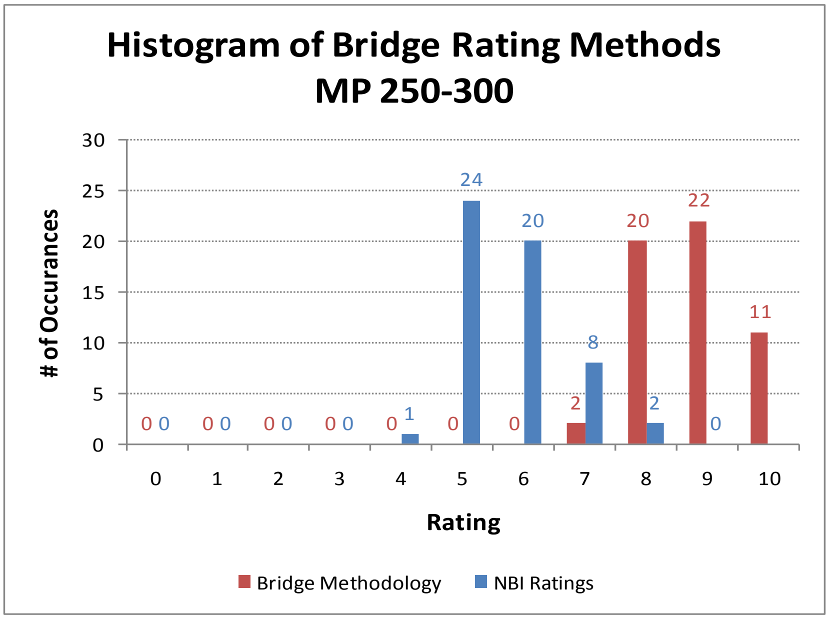

Figure 31: Histogram of NBI and Bridge Methodology Ratings MP 250-300

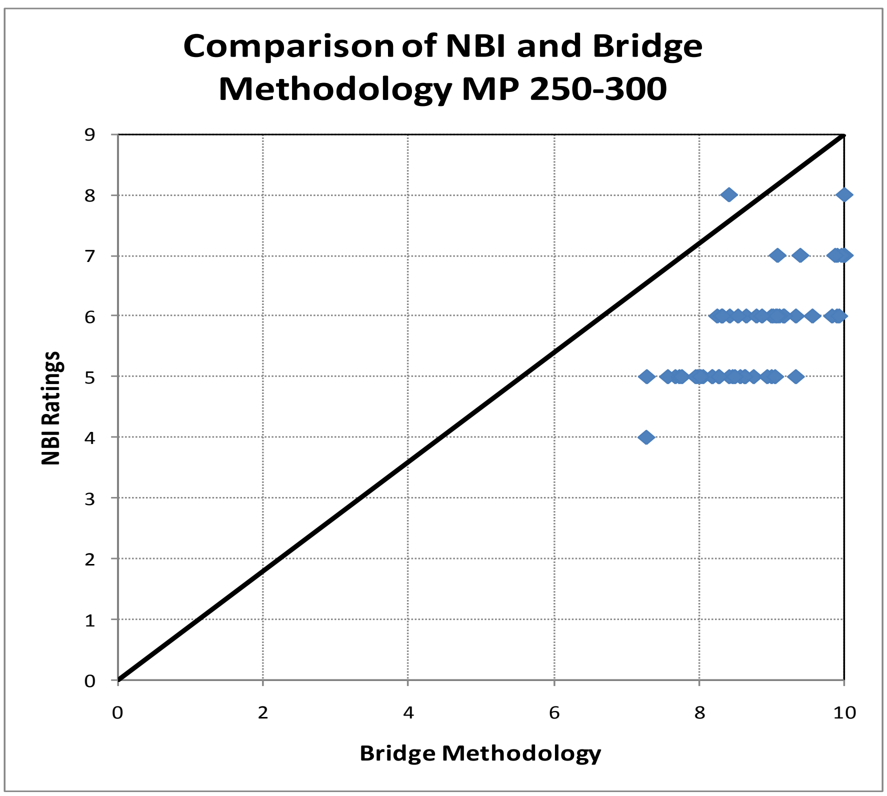

Figure 32: Comparison of NBI and Bridge Methodology on Individual Bridges MP 250-300

A detailed analysis of the results showed that quantities in different condition states of the deck and primary members were the main difference in the BR values. Bridges with all quantities of these two elements in condition state 1 were rated a 10. Bridges with most of these element quantities in condition state 3, 4 and 5 were rated much lower at BR values of 6 and 7. However the NBI ratings for these bridges had the same value of 5.

The analysis suggests that the use of NBI ratings probably does not properly represent the current condition of bridges in the United States. Without using element-level inspection data the ratings do not capture the true health of the structure. As shown, the difference in ratings between two bridges of vastly different condition is not captured by the NBI. The lack of detail in the NBI rating is why some states have begun to use bridge health indexes (BHI) for MR&R action, similar to the proposed bridge rating methodology presented in this thesis. The BHI is a rating based on greater detail and is much more sensitive to changes in condition of critical bridge elements.

5.3.7. **Corridor Section Bridge Health Rating Results**

The last step in the bridge rating process is to calculate the BHR for the entire corridor section using Equation (22). Individual BHR ratings were used to calculate the final BHR. The first step in the calculation was to take the individual BHR ratings and multiply by the total deck area. For the sample bridge shown in Tables 26 through 31, the calculated BHR was 7 and the deck area was 573.6 ft^2. Multiplying these two values together resulted in a value of 3908.02. All of these values calculated for the bridges were then summed together to get a total value for the network. This was then divided by the total deck area for the corridor section. Table 32 presents the results of these calculations for each corridor section.

Also calculated was the pure average of the bridge conditions. This was compared to the weighted average to see if there was a significant difference. The results are shown in Table 33. The result shows that the weighted average had lower values than the pure average. This demonstrates that the weighted average captures the lower condition of larger bridges in the network.

Table 32: Final BHR Values for Corridor Sections

SECTION	∑(BHR*A_b)	∑(A_b)	FINAL SECTION BHR
MP 50-100	421968.67	50507.19	**8.4**
MP 250-300	391986.55	45101.76	**8.7**

Table 33: Comparison of Bridge Rating Combination Techniques

SECTION	Weighted Average	Pure Average
MP 50-100	8.35	8.41
MP 250-300	8.69	8.79

As shown in Table 32 the bridges in section MP 250-300 are in slightly better condition or health than those in section MP 50-100. Because of their overall lower rating, the bridges between MP 50-100 would have a higher priority than those in the other section. A section in lower condition with more bridges will be more of a priority than a section in better condition with fewer bridges.

Use of this tool will help in making network level decisions for bridge repair in a network. As previously discussed in section 5.3.6 the use of NBI as a national reporting and decision making tool does not appear to be sufficient. Using the proposed bridge rating methodology will provide a rating based on element level inspections that show the variation in condition of important structural elements. The method will still rely on skilled bridge inspectors to provide quality data to be used in the condition calculation. The data collected by these inspectors will need to be in greater detail, hopefully reducing inspector opinion and bias.

The proposed bridge rating method will provide a new tool to help in fund allocation for the repair of bridges across the United States and could be a feasible replacement for the current NBI rating practices.

5.4. *Corridor Health Rating Results*

The final step in the corridor rating methodology is to combine the corridor section asset-specific health ratings, PHR and BHR, into a single value. The corridor health rating (CHR) will represent the current health of all the assets located in the corridor section. As outlined in section 3.5.5 and Equations (25) and (26) the basis of the combination will be both the surface areas and unit replacement cost of pavements and bridges.

The costs used for this project were based on values obtained from VDOT. The base cost used for pavements was $1,000,000 per lane mile. For bridges, VDOT estimates the cost to replace the entire bridge structure based on the area of the bridge deck. This cost was provided at $576 per square foot of deck area. These costs can be updated to reflect changes in material, labor, and construction costs.

Using these costs and the total length of pavement and deck area of bridges the coefficients C_b and C_p can be calculated using Equation (26). These values were then used in Equation (25) to calculate the overall CHR for each of the two test corridor sections. For these calculations the length of the section is approximately 50 miles, but the total length for both northbound and southbound directions will be used.

The values of C_b and C_p are calculated as a decimal number which represents what percentage of each asset's contribution to the cost to replace all the assets in the section. The coefficients are influenced by which asset has the highest cost to replace and higher quantity. Using this method the asset which costs more to replace within the section has more influence on the overall condition of the section. After analysis of the data for the two sections values of C_b and C_p were obtained for each corridor section. These results are presented in Table 34.

Table 34: Values of Coefficients for Corridor Sections

SECTION	Length of Pavement (miles), L_p	Area of Bridge Deck (ft^2), A_b	Pavement Coefficient, C_p	Bridge Coefficient, C_b
MP 50-100	100.06	50306.20	0.775	0.225
MP 250-300	100.03	45101.76	0.794	0.206

The values show that the pavement has more effect on the overall health of the corridor section. As expected, the value of C_b is higher in the section with more bridge deck area. These values are based on the prices provided by VDOT. If this methodology is to be used at the national level the prices could be set as the national average or changed on a state by state basis.

Using these values, the overall CHR can be calculated with Equation (25). These results along with the final ratings for pavements and bridges are provided in Table 35.

Table 35: Overall values of CHR for Corridor Sections

SECTION	PHR	BHR	FINAL CHR
MP 50-100	7.98	8.36	**8.06**
MP 250-300	7.91	8.69	**8.07**

From the results, it can be concluded that the overall condition of the two test corridor sections is similar. This result is understandable since the two sections are on the same interstate route and under the same jurisdiction. It is possible that all the sections on I-81 in Virginia are in similar condition due to similar MR&R plans. Other sections would need to be tested in order to verify this result.

5.5. *Method Application Summary*

The results of the demonstration show that this methodology can be a valuable tool for rating the health of assets within a corridor. The ratings provide a single value that shows the overall condition of all the assets of interest within a corridor section. Although the test sections provided a similar overall CHR value, the method itself has shown that values can be calculated based on cost to replace.

In addition to the overall CHR ratings, the methods used to calculate the pavement and bridge ratings show promise as a way to objectively rate these assets. The CCI ratings followed a similar trend as the pavement SR values. The bridge ratings had much more variation than the NBI ratings; however this might be closer to actual conditions. As a general framework both asset rating systems have proven they can be used as an effective method.

Another benefit of the CHR values is the ability to include additional assets as more reliable rating methods become available. Toll plazas, weigh stations, signage, pavement markings, etc. can all be added to the final condition rating as a percentage of their cost of replacement in comparison to the total cost to replace the section. Assets can be added if they have the same rating scale as the assets already included in the methodology. This will allow for the development of a health index more closely related to the overall user experience.

The ratings demonstrated in this chapter have shown that the methodology can be applied to calculate values for use in comparing corridor sections across the country. This comparison can help in identifying bad health sections on not only the IHS routes but the NHS routes as well.

CHAPTER 6: **Summary and Conclusions**

The literature review has shown that current practice for condition ratings varies from state to state. This lack of consistency between agencies has made it difficult to compare conditions of assets across the nation. The NBI is an example of a national rating system that is currently used and has been the standard for over 40 years. However, this researched showed the NBI might be ineffective in thoroughly distinguishing between varying bridge conditions. There is a need for a rating method that can be applied to multiple assets across the nation to allow for easier comparison and better asset management. The method outlined in this project can meet this need. It provides a way to rate assets, such as pavements and bridges, in an objective manner and allows for the combination of assets into a single rating for corridor sections.

6.1. *Findings*

The key finding from the literature review is the great variation in the way assets are rated across the nation. For pavements a total of 21 rating methods were displayed in Table 3 and many more exist. Lack of consistency of scales and condition data used in the rating methods makes it difficult to compare values between states. Some common ground can be found between states, however they usually do not use both the same scale and condition data. Two states may have the same scale but the amount of data used or collected will be different.

For bridges, this thesis has demonstrated that the NBI might not be sensitive enough to changes in condition. Although the available scale goes from 0 to 9, the majority of reported ratings ranged between 4 and 7. As shown in the thesis, two bridges with greatly varying element level condition of the major structural components can have the same NBI rating. One of the bridges would be a more likely candidate for MR&R action than the other, which is not reflected by the NBI. The rating system needs to be improved to be more sensitive to changes in the condition of critical elements.

The main conclusion is that current practice in asset rating has not been consistent enough to compare ratings accurately among states. The methodology developed for this thesis can help to create consistency across the U.S. The framework can help to allow for comparison of assets and assist in IMS practices at the corridor level.

6.2. *Products*

The objective of the thesis was to develop a framework for the health rating of corridors as well as the individual asset health ratings. The framework was then implemented in a pilot study and used to calculate pavement, bridge, and corridor health ratings using VDOT data. The products of this project are as follows:

- Analysis of available asset health rating techniques
- Generalized Corridor Rating Framework
- Pavement Rating Methodology Demonstration
- Bridge Rating Methodology Demonstration
- Corridor Rating Methodology Demonstration

The method combines individual asset health ratings, such as those developed for pavement and bridges, into a final overall rating for sections of a corridor. The method is designed to take assets rated on a common scale and create a final rating based on the relative cost of replacement for each asset. The percentage of an asset's cost to replace compared to the corridor's overall cost reflects what weight the asset's rating has in the final overall health index.

A secondary goal of the project was to create a consistent method that uses objective data to accurately rate the health of individual assets. The goal was to have a consistent scale that allows comparison of assets between states and easy combination of different assets into a corridor health index. This goal was met successfully and the final products were two rating methods that can be used with currently collected data.

These products are the first steps in moving towards corridor level health rating systems being created and employed in the United States. Use of these rating methods can help to better manage the condition of the entire road network of the United States. It can also allow states to compare conditions of their assets with other states. This could result in better collaboration and adaptation of new MR&R methods that have been shown to improve condition.

6.3. *Recommendations for Facilitating Implementation*

For the methodology to be adopted there will need to be changes to the ways data is collected. These changes will need to be made at the National policy level to ensure that every state is collecting the same, or at least similar, data at the same quality and detail levels.

To effectively employ the proposed pavement methodology data will ideally need to be collected at every tenth mile segment along the NHS network. Currently for the HPMS the data is sampled randomly from a route based on its length and traffic. IRI is continually collected but cracking and rutting are randomly sampled. The HPMS could be changed to require data to be continually collected at every segment along a route. Technology can help to make this a possibility. Data collection vans can automatically and continuously collect all of these data measures. The equipment can be expensive but as the technology expands the price to own this equipment should drop.

The pavement data used in the proposed methodology can be a sampling of the data in a corridor section if continual collection is expensive. The sample of the data would be used as the quality measure that goes into calculating PIs. The main difference would be the length of the section being analyzed. Sampling of data may be a more cost effective method to help with implementing the proposed health rating framework.

The proposed bridge methodology is based on element level condition data. Some states are currently collecting this data for in house use but for the method to be used nationally every state will need to perform element level inspections. These inspections can take more time to complete but provide a more detailed report than the NBI. To make the method effective a required list of elements to be inspected in detail would need to be established. This would ensure that all bridges would have reported data for a crucial set of elements. These elements included in the inspection report can then be used in the bridge methodology to calculate bridge ratings.

AASHTO has already started to provide requirements for element level inspection. In early 2010 the Subcommittee on Bridges and Structures posted a preliminary manual titled “Bridge Element Inspection Manual”. This document outlines the use of element level inspections and defines condition states for several elements common among bridges. This could result in more states collecting data in this manner. The document could be a start towards requiring states to report element level inspection data.

These changes in policy would be necessary to ensure that the data being collected is consistent from state to state. A consistent rating methodology won’t be possible without consistent data collection.

6.4. *Recommendations for Future Research*

The work performed in this thesis can be continued to include rating methodologies for additional roadway assets. Methods for other assets are starting to be developed but are not common enough to be employed at this time. As these methods are developed and data for these assets are more commonly collected they can be incorporated into the corridor rating methodology.

Furthermore as more bridge and pavement data becomes readily available on a national level more data items can be incorporated into the proposed methodologies in this thesis. Weight and element factors would need to be added and adjusted to include these items.

Another area of future interest is in how the performance indicators are combined into health indicators. Comparing the proposed combination techniques with those used in rating methods such as the COST method could help to improve the framework. The current method takes the weighted average of all the performance indicators. The COST method takes the worst performance indicator then reduces the rating based on the other performance indicators.

The proposed methodology provides a general rating for the condition of the overall corridor section. For this purpose, details about the condition of the individual asset types in each section. To identify the individual asset in worst condition in a section, the use of a normal distribution could help to show the range of ratings for an asset type in each section. The use of a standard deviation could be used to flag sections. The distribution's standard deviation could potentially be used as a way to identify which sections have the worst rated single assets.

The addition of parallel routes to this methodology is also a possibility. The current project focused on the condition of IHS routes. Most IHS routes have parallel routes that follow them and carry traffic during times of congestion and traffic. Knowing the condition of these routes or incorporating them into the overall methodology could prove to be useful.

To ensure the quality of the proposed methodology, the framework could be validated through outside sources. Experts could rate the sections independently and their ratings could be compared to those calculated by the proposed framework. Also user panels could be used as another source to compare the proposed ratings to the public's perception.

The proposed future work can provide more depth to the methodology and help to give condition reports to all major assets in as great of detail as possible.

CHAPTER 7: **RESOURCES**

AASHTO. (2001). *Pavement Management Guide*. American Association of State Highway and Transportation Officials, Washington, DC.

AASHTO. (2003). (Release 4). *Pontis Bridge Management User Manual*. American Association of State Highway and Transportation Officials, Washington, DC.

AASHTO. (2007). “AASHTO Bridgeware.” *AASHTOWare*. , American Association of State Highway and Transportation Officials, <http://aashtoware.org/?siteid=28&pageid=75>. (Accessed March 17, 2009)

ASTM (2003). *Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys*. ASTM D6433-03. American Society for Testing and Materials. West Conshohocken, PA.

COST. (2008). *COST Action 354 – Performance Indicators for Road Pavements*, European Cooperation in the field of Scientific and Technical Research, FSV – Austrian Transport Research Association, Vienna, Austria.

FHWA. (1999). *Asset Management Primer*. Federal Highway Administration, Office of Asset Management, Infrastructure Core Business Unit.

FHWA. (2002). *Life Cycle Cost Analysis Primer*. Federal Highway Administration, Office of Asset Management, Infrastructure Core Business Unit.

FHWA. (2008). *HPMS Reassessment 2010+*. Federal Highway Administration Office of Highway Policy Information

FHWA. (2008). 2008 Status of the Nation's Highways, Bridges, and Transit: Condition and Performance, Report to Congress, Executive Summary. Downloaded from http://www.FHIwa.dot.gov

FHWA. (1995). Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges. Office of Engineering, Bridge Division.

Flintsch, G.W., Bryant, J.W. (2009). *Asset Management Data Collection for Supporting Decision Processes.* FHWA Report, Office of Asset Management, FHWA, USDOT, Washington, D.C.

Flintsch, G.W., McGhee, K.K. (2009). *Quality Management of Pavement Condition Data Collection*. NCHRP Synthesis 401. Transportation Research Board, Washington, D.C.

Haas, R., Hudson, W.R., Uddin, W. (1997). *Infrastructure Management*. The McGraw-Hill Corporation, New York, New York.

Hammad, A., Yan, J., Mostofi, B. (2007). "Recent Development of Bridge Management Systems in Canada." Annual Conference for the Transportation Association of Canada. Transportation Association of Canada, Saskatoon, Saskatchewan

Hawk, H (2000). "BRIDGIT: USER-FRIENDLY APPROACH TO BRIDGE MANAGEMENT" Transportation Research Circular No. 498

Hearn, G., Puckett, J., Friedland, I., Everett, T., Hurst, K., Romack, G., Christian, G., Shepard, R., Thompson, T., Young, R. (2005). *Bridge Preservation and Maintenance in Europe and South Africa*. International Technology Exchange Program, FHWA, Washington, D.C.

Hudson, W.R., Hudson, S.W. (1994) “Pavement Management Systems Lead the Way for Infrastructure Management Systems.” *Third International Conference on Managing Pavements*, San Antonio, TX, Transportation Research Board, Washington, D.C.

Janoff, M., Nick, J., Davit, P., and Hayhoe, G. (1975). *Pavement Roughness and Rideability*. NCHRP Report 275, September.

Kang, M.K., Adams, T.M. (2010). *Sensitivity Analysis of Bridge Health Index by Various Element Failure Costs and Element Conditions*. Transportation Research Board 89th Annual Meeting (CD-Rom). TRB, Washington, D.C.

Lemer, A.C. (2004). *Public Benefits of Highway System Preservation and Maintenance: A Synthesis of Highway Practice*. NCHRP Synthesis 330. Transportation Research Board, Washington, D.C.

McGhee, K.H. (2002). Development and Implementation of Pavement Condition Indices for the Virginia Department of Transportation. Virginia Department of Transportation, Richmond, VA.

National Cooperative Highway Research Program (NCHRP). (2009). *Report 632 – An Asset-Management Framework for the Interstate Highway System*. Transportation Research Board, Washington, D.C.

New York State Department of Transportation (NYSDOT). (1999). *New York State Bridge Inspection Manual*. Albany, NY.

Optimizing Highway Performance: Pavement Preservation. (2000). Construction and Maintenance Fact Sheets, Report FHWA-IF-00-013, Federal Highway Administration, Washington, D.C. [Online]. Available: http://www.fhwa.dot.gov/construction/fs00013.cfm

OECD. (1987). *Pavement Management Systems*. Organization for Economic Cooperation and Development, Paris, France.

PAVER Asphalt Distress Manual, US Army Construction Engineering Laboratories, TR 97/104, June 1997.

Papagiannakis, A., Gharaibeh, N., Weissmann, J., Wimsatt, A. (2009). "Pavement Scores Synthesis." *Evaluation and Development of Pavement Scores, Performance Models and Needs Estimates*, Texas Transportation Institute, College Station, TX.

Robert, W.E., Marshall, A.R., Shepard, R.W., Aldayuz, J. (2003). "Pontis Bridge Management System: State of the Practice in Implementation and Development." *9th International Bridge Management Conference*, Transportation Research Circular, Washington, DC, 49-60

Shepard, R., and Johnson, M. (2001). "California Bridge Health Index: A Diagnostic Tool to Maximize Bridge Longevity, Investment." TR News, Issue 215, p. 6-11.