Evaluation of Highway Performance Measures for a Multi-State Corridor – A Pilot Study

U.S. Department of Transportation
Federal Highway Administration
Office of Asset Management

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Foreword

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16. Abstract

Determining an appropriate set of performance measures to use for managing the nation's highway network is a vital component of the work to preserve our existing transportation infrastructure. Recent research, such as National Cooperative Research Program (NCHRP) Project 20-74 describing an asset management framework for the Interstate Highway System (IHS), has highlighted the importance of establishing a consistent set of performance measures for communicating physical conditions of our roads, bridges, and other highway assets.

The Federal Highway Administration (FHWA) Office of Asset Management developed this project to analyze bridge and pavement data across a multi-state corridor, evaluate the quality of existing performance measures, and recommend additional measures as well as further avenues of research in this area. A key deliverable involved using the Integrated Corridor Analysis Tool (ICAT), previously developed by the I-95 Corridor Coalition, as a platform to display bridge and pavement performance data. ICAT provides a map-based application, accessible via the Internet, that allows users to view, analyze and compare performance data along an entire corridor or at a specific location.

This project provides a statistical analysis of bridge and pavement data received from Virginia, Maryland and Delaware. This analysis included looking at individual values as well as comparing values both within a state and across states.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

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

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

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Executive Summary

Determining an appropriate set of performance measures to use for managing the nation's highway network is a vital component of the work to preserve our existing transportation infrastructure. Recent research, such as National Cooperative Research Program (NCHRP) Project 20-74 describing an asset management framework for the Interstate Highway System (IHS), has highlighted the importance of establishing a consistent set of performance measures for communicating physical conditions of our roads, bridges, and other highway assets.

The Federal Highway Administration (FHWA) Office of Asset Management developed this project to analyze bridge and pavement data across a multi-state corridor, evaluate the quality of existing performance measures, and recommend additional measures as well as further avenues of research in this area. A key deliverable involved using the Integrated Corridor Analysis Tool (ICAT), previously developed by the I-95 Corridor Coalition, as a platform to display bridge and pavement performance data. ICAT provides a map-based application, accessible via the Internet, that allows users to view, analyze, and compare performance data along an entire corridor or at a specific location.

For this project, Cambridge Systematics (CS) performed a statistical analysis of bridge and pavement data received from Virginia, Maryland, and Delaware. This analysis included looking at individual values as well as comparing values both within a state and across states. CS concluded that:

- International Roughness Index (IRI) does not provide adequate information to judge overall pavement condition;
- Composite measures of pavement condition (i.e., measures that combine multiple distress readings into a single number) are better than individual measurements but still may not correlate well with structural adequacy; and
- Sufficiency rating and health index both provide adequate, albeit slightly different, measures of the condition of a bridge.

Based on the analysis and conclusions, CS recommended that FHWA:

- Modify the National Bridge Inventory (NBI) to obtain element data from states and use these data to calculate bridge health index on a national level;
- Develop one or more health index calculations for pavement using Highway Performance Monitoring System (HPMS) 2010+ data elements;
- Test sample road sections to determine whether a relationship exists between pavement health indexes and actual road condition and use this information to develop a true measure of structural adequacy for pavement; and
- Define models of roadway functional obsolescence and public importance that are simple to use and interpret.

1.0 Introduction

1.1 Overview

The goal of the project was to integrate pavement and bridge performance data from a multi-state corridor to facilitate analysis of performance measures, and to evaluate how performance data can be used for corridor management.

The project consisted of the following four tasks:

- Task 1 – Data Acquisition and Analysis Plan;
- Task 2 – Data Collection and Integration;
- Task 3 – Analysis and Evaluation of Alternative Condition Indicators; and
- Task 4 – Develop Condition Indicator Display Capability.

The results of each task are detailed in this report.

1.2 Report Organization

The remainder of this report is organized as follows:

- **Section 2** summarizes the results of the data acquisition and analysis task. It presents the plan for acquiring pavement and bridge data and the scope of the data collection effort.
- **Section 3** summarizes the results of the data collection and integration task.
- **Section 4** summarizes the results of the analysis and evaluation of alternative condition indicators task. It recommends how cross-state asset data should be analyzed to support decision-making and discusses the degree to which cross-state comparisons can be made based on the sample data collected through Task 2.
- **Section 5** documents the design report for adding condition indicators to the Integrated Corridor Analysis Tool (ICAT) developed by the I-95 Corridor Coalition and lists any other ICAT changes to support this enhancement.

2.0 Data Acquisition and Analysis Plan

This section presents the plan for acquiring pavement and bridge data from the states in the I-95 Corridor Coalition.

2.1 Scope of Data Collection Effort

States

The Federal Highway Administration (FHWA) and the project team identified the following three states along the I-95 Corridor for the analysis of highway performance measures: Delaware, Maryland, and Virginia. Cambridge Systematics, Inc. (CS) contacted the states and all agreed to provide their pavement and bridge data. We have completed the process of gathering data from the states.

Available Data

Table 2.1 displays the available sources of pavement and bridge data from the three states that CS has collected.

Table 2.1 Available Data from States

State	HPMS	PMS Data	NBI	Pontis BMS Data	Other BMS Data
Delaware	√	√	√	√	
Maryland	√	√	√		√
Virginia	√	√	√	√	

The following paragraphs describe each data source. At the national level, the pavement data are available through the Highway Performance Monitoring System (HPMS) and the bridge data through the National Bridge Inventory (NBI). Most agencies collect additional pavement and bridge data that go beyond Federal requirements in database-driven systems such as a pavement management system (PMS) and/or a bridge management system (BMS).

- **HPMS.** HPMS includes inventory, performance, and condition data for the nation's highways. States are required to collect and submit these data to the FHWA annually. Present Serviceability Rating (PSR) and International Roughness Index (IRI) are the only pavement condition measures reported in HPMS. HPMS does not include pavement distress data such as rutting, cracking, or faulting. However, many states do collect these additional data and employ an overall pavement condition index that is agency-specific. The

HPMS Reassessment 2010+ effort will add a number of pavement distress measures, and standardize data collection and reporting requirements.

- **PMS.** Most states have developed custom pavement management systems that they use to store inventory, condition, traffic, work history, and cost data. Since there are no standards on how these data are stored, the PMS specification varies widely from state to state.
- **NBI.** NBI includes the inventory, condition, and functional data for the nation's highway bridges. States are required to inspect bridges biannually and submit these data to the FHWA every year. More frequent inspections are performed if warranted based on condition. The NBI dataset contains condition ratings for deck, superstructure, substructure, channel/channel protection, and culvert.
- **BMS.** Pontis includes element-level inspection data as well as NBI data. Element-level data provide more detailed bridge condition information. Many states use AASHTO's Guide for Commonly Recognized (CoRe) Structural Elements for element definitions and condition state language, but states may create their own custom elements and/or modify the CoRe element definitions. Virginia and Delaware collect element-level bridge data using Pontis. They also have added agency-specific data items to the Pontis database. Maryland has its own BMS that stores element-level data.

Additional Research

In order to obtain a comprehensive view of the data collected by states, CS held additional discussions with pavement and bridge personnel in each state. The goal of these discussions was to more fully understand the process that each state uses to gather the data (e.g., what technologies are used, under what circumstances are inspections performed, how are data validated) and what constraints govern the use of these data.

For example, the completeness and accuracy of pavement data gathered as part of a visual inspection will differ from data gathered using automated electronic recorders. Users of the data need to understand these limitations in order to properly interpret the data that is available. This information is included in the Data Collection Report found Section 4.2 of this document.

2.2 Data Collection Methodology

In order to collect the pavement and bridge data necessary for this study, CS contacted key personnel in the candidate states and requested that they provide information from their pavement and bridge management systems, respectively. Specifically, CS requested a complete set of condition data, including element-level information for bridges and all measured or computed values for pavement, for all bridges and roads covered by these systems. If states felt that the effort to provide these data would be burdensome, CS requested, at a minimum, pavement and bridge data for the I-95 corridor.

Table 2.2 summarizes the information received and the persons that provided this information. These persons also served as the main points of contact to clarify data already received and to obtain additional information regarding the inspection and quality assurance processes used by each state agency.

Table 2.2 Sources for Pavement and Bridge Data

State	Data Received	Contact Person
Delaware	Bridge Data – a Pontis database containing NBI and element-level condition information for all bridges in the state.	Douglas E. Finney, P.E. Bridge Management Engineer Delaware DOT (302) 760-2314 Doug.Finney@state.de.us
	Pavement Data – a Microsoft Excel spreadsheet containing IRI and overall pavement condition (OPC) values for the Delaware road network.	Kim Johnson Pavement Management Delaware DOT (302) 760-2067 Kimberly.Johnson@state.de.us
Maryland	Bridge Data – a Microsoft Excel spreadsheet containing element condition data for the state-owned bridges on I-95 only. State-owned bridges make up approximately one-half of the I-95 bridges. The other bridges are owned by the Maryland Turnpike Authority.	Robert J. Healy Deputy Director, Office of Structures Maryland State Highway Administration (410) 545-8063 RHealy@sha.state.md.us
	Pavement Data – a Microsoft Excel spreadsheet containing IRI, rutting, cracking and friction values and indexes for I-95 only.	Mark F. Wolcott, P.E. Deputy Director for Material Engineering Maryland State Highway Administration (443) 572-5036 MWolcott@sha.state.md.us
Virginia	Bridge Data – a Pontis database containing NBI and element-level condition information for all bridges in the state.	Anwar S. Ahmad, P.E. Assistant Division Administrator Virginia DOT (804) 786-2853 Anwar.Ahmad@vdot.virginia.gov
	Pavement Data – a Microsoft Access database containing data on transverse and longitudinal cracking, alligator cracking, clustered cracking, patching, potholes, delaminations, bleeding, rut depth, load distress ratings, shoulder conditions, and other values for the Virginia interstates.	Tanveer Chowdhury, P.E. Assistant Division Administrator Maintenance Division, VDOT (804) 786-0694 Tanveer.Chowdhury@vdot.virginia.gov

2.3 POTENTIAL ISSUES WITH DATA

Even though HPMS and NBI reporting requirements provide a consistent standard for collecting pavement and bridge data, in reality the level of detail for these data varies significantly from state to state. Furthermore, it is much harder to compare state-specific data items that are outside of HPMS and NBI due to a lack of national standard and guidelines. States may have distinct agency policies, such as different thresholds for identifying deficiencies.

- Many states use an overall pavement condition index to represent average pavement condition, but there is no specific standard for calculating this measure.
- States often use automated road profiling instruments that measure road characteristics and calculate surface smoothness. Due to different equipment used by the states, the pavement condition data being collected are not based on the same specification.
- HPMS sample data are not collected for all interstate highway sections.
- The number of pavement values collected varies widely by state, which limited the number of state-to-state comparisons that were made.
- Visual inspection of pavement and bridges can be subjective, and the inspector training is different from state to state.
- Comparing health index across states can be problematic due to a lack of consistency in element definitions. States may modify the CoRe element definitions and add their own custom elements.

Addressing issues such as these was a main thrust of this project.

2.4 ICAT Integration

The goal of Task 2 was to integrate data from states into ICAT. This process, discussed in Section 3, included a more complete analysis of the data available from each state. Part of the integration with ICAT involved resolving discrepancies between the ICAT network and the routes and other location information included in the bridge and pavement data collected from participating states. At a minimum, this required that CS ensure each route in ICAT had a unique identifier across all states and that there was sufficient information in the pavement and bridge data to reproduce this identifier. This allowed pavement and bridge data to be linearly referenced against the ICAT road network.

Once a route system was built from the ICAT road network, dynamic segmentation techniques were used to categorize and overlay the pavement and bridge data. These overlays were published as standalone files that were incorporated into the web-based ICAT (WebCAT) interface as part of Task 4, which is discussed in Section 5. Users can select from and display categorized performance measures as well as displaying raw data for any bridge or pavement section.

For Task 3, CS established candidate performance measures that summarize the detailed pavement and bridge data. CS also performed any necessary data calculations and transformations to compute these measures using the available data. The following is a list of statistical functions that were used to evaluate the quality, consistency, and completeness of the pavement and bridge data.

For individual measures, CS:

- Calculated the minimum, maximum, mean, median, variance and number of data points;

- Plotted the probability and cumulative distribution functions;
- Performed calculations separately with each pavement section or bridge having equal weight and weighted using deck area for bridges and section length for pavements; and
- Performed calculations separately for each state and combined across states where the same measure is collected in multiple states.

For reasonable combinations of measures, CS:

- Calculated the correlation coefficient for scalar measures that appear to be correlated;
- Calculated the correlation coefficient of the rank for categorical measures that appear to be correlated; and
- Performed these calculations separately for each state as well as combined where the same measure is collected in multiple states.

For bridges, the following combinations were considered:

- Health Index versus Sufficiency Rating; and
- Deck/superstructure/substructure condition index versus condition ratings (converted into ranks).

For pavement, the only measure common across all three states is IRI. It was not possible to compare rutting and cracking between Maryland and Virginia because these states record these values using different measures (e.g., index values versus linear feet of cracking).

CS also considered other possible indicators that could be created if additional information were available. For example, values such as load capacity (per unit surface area) and remaining service life could be constructed from information on pavement composition and/or maintenance history. In Section 4.4, CS suggested future areas of research for consideration by FHWA.

In Task 4, CS developed the means to display bridge and pavement data and performance measures within the WebCAT web application. This application uses Geographic Information System (GIS) processes to display the network of roads in I-95 member states. WebCAT also is capable of displaying information associated with these roads.

CS reviewed information collected previously by the I-95 Corridor Coalition for incorporation into ICAT. The existing database includes geospatial data, HPMS data, and NBI data. We leveraged this previous work when integrating the data collected for this project with ICAT. As part of incorporating the new pavement and bridge data received from Virginia, Maryland, and Delaware, CS extended the ICAT tables to include not only the superset of all the data elements received from these states, but additional performance measures that were calculated from these elements.

3.0 Data Collection and Integration

This section details the results of the data collection effort described in Section 2. Observations regarding the structure and content of the pavement and bridge data are presented. This section also contains information on how these data have been integrated into the ICAT repository.

3.1 Data Collection Results

CS completed the data collection process, described in Section 2, on Wednesday, December 9, 2009. CS received the following data:

- Virginia:
  - Bridge Data: a Pontis database containing National Bridge Inventory (NBI) and element data for all Virginia bridges. This information was collected by Virginia primarily in 2009.
  - Pavement Data: a Microsoft Access database containing pavement segments (identification, location, condition) for all Virginia interstates. This information was collected by Virginia primarily in 2008.
- Maryland:
  - Bridge Data: a Microsoft Excel spreadsheet containing element data for bridges on I-95 maintained by the Maryland State Highway Administration. This information was collected by Maryland primarily in 2008. (Note: additional bridges on I-95 owned by the Maryland Turnpike Authority were not provided.)
  - Pavement Data: a Microsoft Excel spreadsheet containing pavement segments (identification, location, condition) for I-95 in Maryland. This information was collected by Maryland primarily in 2007. Due to a systemic issue with the 2008 pavement data, Maryland elected to provide 2007 data.
- Delaware:
  - Bridge Data: a Pontis database containing NBI and element data for all Delaware bridges. This information was collected by Delaware primarily in 2008.
  - Pavement Data: a Microsoft Excel spreadsheet containing pavement segments (identification, location, condition) for state-managed roads and

highways in Delaware. This information was collected by Delaware primarily in 2008.

- Other:
  - NBI data for all Maryland bridges (FHWA web site);
  - NBI and element data for all District of Columbia bridges (Pontis database); and
  - Highway Performance Monitoring System (HPMS) data for Virginia, Maryland, and Delaware (FHWA web site).

3.2 DATA STRUCTURE AND CONTENT

Bridge Data

Virginia and Delaware bridge data were provided as Pontis databases. The Delaware bridges are contained in a Sybase Adaptive Server Anywhere database file while the Virginia bridges were delivered in an Oracle database export file, which CS has loaded into an Oracle database. These Pontis databases contain NBI and element data, stored in a hierarchical collection of tables, for all bridges in their respective states. The Virginia database contains 22,454 bridges of which 363 are on I-95. The Delaware database contains 1,606 bridges of which 59 are on I-95.

Maryland bridge data were provided in a Microsoft Excel spreadsheet. This spreadsheet contained the following items:

- Structure Number (NBI Item #8);
- Record Type (NBI Item #5A);
- Route Number (NBI Item #5D);
- Inspection Date (NBI Item #90);
- Element ID;
- Element Total Quantity;
- Element Quantity in Condition State 1;
- Element Quantity in Condition State 2;
- Element Quantity in Condition State 3;
- Element Quantity in Condition State 4; and
- Element Quantity in Condition State 5.

The spreadsheet includes one record for each combination of Structure Number and Element ID. A total of 2,269 records were provided. These records represent 118 structures. All of these structures are "on" (Record Type = 1) I-95. In addition, Maryland provided a document, the *Pontis Element Data Collection Manual* prepared by the Maryland Department of Transportation State Highway Administration Office of Bridge Development, revised July 2003, which describes the State's elements, condition state definitions, and available actions.

In order to facilitate calculation of values such as health index, CS converted the Maryland bridge information into a Pontis database. CS began by loading the Maryland NBI data for all bridges into a blank Pontis database. CS then used a manual process to create a single element inspection based on the spreadsheet information for each of the 118 I-95 bridges. Most of the elements received from Maryland exactly matched Commonly Recognized (CoRe) elements available in Pontis. However, Maryland has defined 15 elements that are not in Pontis. CS created custom elements in Pontis to accommodate these records.

In addition to the bridge data provided by Virginia, Maryland, and Delaware, CS reviewed bridges for the District of Columbia. The source for these bridges was a Pontis database last updated during the summer of 2008, which already was available to CS. After this review, it was determined that the D.C. Pontis database did not contain any bridges on I-95.

Pavement Data

Virginia provided pavement information in a Microsoft Access 2000 database. This database contains three tables for different types of pavement, including Asphalt Concrete Pavement (ACP), Continuously Reinforced Concrete Pavement (CRCP), and Jointed Reinforced Concrete Pavement (JRCP). These tables include common columns that identify the pavement segment location, physical characteristics, and inspection information. The only condition measures included in these standard columns are International Roughness Index (IRI) left, right, and average, and Critical Condition Index (CCI).

In addition to IRI and CCI, each table contains condition measures unique to the pavement type. For example, the ACP table includes these additional measures:

- Transverse Cracking Severity 1;
- Transverse Cracking Severity 2;
- Longitudinal Cracking Severity 1;
- Longitudinal Cracking Severity 2;
- Longitudinal Lane Joint Severity 1;
- Longitudinal Lane Joint Severity 2;
- Reflective Transverse Cracking Severity 1;
- Reflective Transverse Cracking Severity 2;
- Reflective Transverse Cracking Severity 3;
- Reflective Longitudinal Cracking Severity 1;

- Reflective Longitudinal Cracking Severity 2;
- Reflective Longitudinal Cracking Severity 3;
- Alligator Cracking Severity 1;
- Alligator Cracking Severity 2;
- Alligator Cracking Severity 3;
- Patching Area – wheel path;
- Patching Area – nonwheel path;
- Pothole Count;
- Delamination Area;
- Bleeding Severity 1;
- Bleeding Severity 2;
- Average Deeper Rut (straight-edge);
- Average Deeper Rut (wire method);
- Load Distress Rating; and
- Nonload Distress Rating (Note: Load and Nonload Distress Ratings are calculated values and CCI always is the "worst" of these two ratings).

Combined, the three tables in the database appear to contain road segments for all interstates in Virginia. After reviewing these data, CS determined that 192 segments for I-95 were found only in the ACP table. These segments range in length from 0.15 to 9.83 miles with an average length of 1.935 miles. There are no I-95 segments for pavement types CRCP and JRCP. Consistent with our project strategy, the CS analysis used only the I-95 segments from the ACP table.

Maryland provided pavement information in a Microsoft Excel spreadsheet. The spreadsheet contains one workbook holding one-tenth-mile sections and a second workbook holding one-half-mile sections. Both workbooks contain data only for I-95 northbound and southbound. The workbooks are identical in structure and include segment identification and location information and the following measures:

- IRI;
- Rutting Depth;
- Count of Rut Depth > 0.5 inches;
- Cracking Index;
- Friction Number;
- IRI Condition (0, 1-5);
- Rut Condition (0, 1-5);

- Crack Condition (0, 1-5); and
- Friction Condition (0, 1-5).

After reviewing the Maryland pavement data, CS determined that the analysis would focus on 2,179 one-tenth-mile segments for I-95 and the one-half-mile data would not be used.

Delaware provided pavement information in a Microsoft Excel spreadsheet. The spreadsheet appears to contain data for all state-managed roads and highways in Delaware. In addition to route identification and begin/end mile points, the spreadsheet contains the following measures:

- IRI – left and right; and
- Overall Pavement Condition (OPC).

After reviewing all pavement data provided by Delaware, CS determined that 193 segments for I-95 would be used in the analysis. These segments range in length from 0.01 to 1.01 miles with an average length of 0.195 miles.

In addition, CS obtained 2008 HPMS information for Virginia, Maryland, and Delaware. CS compared the HPMS data with the pavement data received from each state. CS did not find any significant gaps in the state data and did not include any of the HPMS information in the analysis.

3.3 Data Issues

CS conducted a review of all the information received from Virginia, Maryland, and Delaware. For the bridge data, no significant issues were uncovered. Bridge inspection and condition reporting has been heavily influenced by the FHWA through the creation of the NBI and by the American Association of State Highway and Transportation Officials (AASHTO) through the creation of Pontis. These standards, and the processes that support them, have resulted in a high degree of uniformity in bridge information available from states.

Uniform bridge data does mean that there are, potentially, fewer avenues to explore as part of the data analysis. Condition ratings, Sufficiency Rating and Health Index continue to be the leading candidates for evaluating the physical condition of a bridge.

For the pavement data, however, there was much less consistency. Currently, IRI is the only condition measure captured by all participating states. As defined in the HPMS Reassessment 2010+, states already should be collecting new data elements and will begin reporting these elements in June 2010. This will provide a larger universe of common information from which to judge pavement structure and condition.

The amount and completeness of pavement data available from a state depends heavily on the inspection process. States with automated inspection capability tend to provide more complete and comprehensive data, which on the surface appears to be more accurate. Inspections that are primarily manual tend to capture fewer data elements. And the very nature of these differing inspection processes virtually guarantees that each state will measure the same value in different ways.

Based on the data alone, it is difficult to determine which inspection process better represents the pavement structure and condition. As shown in Section 4, CS analyzed and compared available data both within a state and across states in an effort to categorize the information and recommend options to FHWA regarding performance measures to support corridor-wide decision-making.

3.4 ICAT Integration

There were two key steps to preparing data for integration into the database for the Integrated Corridor Analysis Tool (ICAT). First, common data structures were defined for bridge and pavement information. Second, CS ensured that sufficient data elements existed to match bridge and pavement records to the existing ICAT network.

For both bridge and pavement data, CS defined data structures in the ICAT repository. For bridges, CS extended the existing NBI record structure with columns that hold other measures such as Health Index (overall and by bridge component). For pavement, CS defined a custom data structure that is a superset of the elements received from Virginia, Maryland, and Delaware.

Both the bridge and the pavement data in ICAT were updated to include computed metrics defined in Task 3. These metrics were placed in columns added to the bridge and pavement tables described above. CS reviewed both the measures and the metrics and selected a subset of them to display within the ICAT web interface (WebCAT). Refer to Section 5 for additional information on this interface and how it can be used to display bridge and pavement performance measures.

CS reviewed the bridge and pavement data and confirmed that sufficient information existed to place these structures on the ICAT road network. For bridges, a combination of NBI Item 5 – Inventory Route, Item 11 – Kilometer Point, Item 16 – Latitude, and Item 17 – Longitude were used to "snap" the bridge to the closest point on the identified route. For pavement, sufficient values were received from each state to reproduce the linear referencing system (LRS) key that was incorporated into the ICAT network when it was built from original state road information. This LRS key, in combination with the beginning and ending mile point, was used to "overlay" the pavement data onto an ICAT route. For some states, CS also had to adjust the mile points to ensure that these values represented a continuous range across the state. For example, the Virginia pavement data reset the mile point to zero at each county boundary. This was not consistent with the mile points used by ICAT.

3.5 DATA ANALYSIS

Task 3 focused on a comprehensive analysis of the bridge and pavement data collected for this project, including reporting information on how the states perform their inspections and control the quality of their data. CS applied a variety of statistical functions to evaluate the quality, consistency, and completeness of the data. Using this information, CS defined candidate performance measures that summarize the detailed bridge and pavement data. CS also performed calculations and transformations to compute other measures using the available data. Refer to Section 4 for the results of this analysis.

In Task 4, CS developed the functionality to display bridge and pavement data and performance measures in WebCAT. Refer to Section 5 for design information showing how the WebCAT web interface allows users to select one or more candidate measures and display categorized pavement and bridge data in Virginia, Maryland, and Delaware.

4.0 Analysis and Evaluation of Alternative Condition Indicators

This section contains the analysis of condition measure data, both bridge and pavement, received from the participating states. The analysis begins with background on the traditional measures used to evaluate these assets before presenting a statistical breakdown of the specific data captured for this project. Condition is one measure of performance. Other performance measures may relate to functional adequacy or overall importance of a given asset.

Following the analysis, CS presents information obtained from the participating states on the processes used to capture bridge and pavement condition information, including methods employed to validate the quality of the data. This section also includes feedback on the state-specific criteria used to categorize asset condition (e.g., as "good," "fair," or "poor").

Finally, CS presents conclusions on the adequacy of the existing measures for bridges and pavement, highlighting some of the results of the data analysis. CS also makes recommendations on alternative indicators and discusses the issues related to adopting different measures.

4.1 Data Analysis

Section 3 discusses the bridge and pavement data that were collected from the states participating in this study. Due to time and budget constraints as well as the fact that Maryland provided data only for Interstate 95, CS generally restricted its analysis to assets present on I-95.

Review of Statistical Functions

This section briefly reviews some of the statistical functions used in the data analysis.

Correlation coefficient indicates the correlation or linear dependence between two variables. The correlation coefficient is defined as the covariance of the variables divided by the product of their standard deviations. It yields a value between -1 and +1. If the correlation coefficient is equal to 0, it means that there is no linear correlation between the variables. A value of +1 or -1 means that there is a linear equation that describes the relationship between the variables. The correlation coefficient is positive if the variables simultaneously are greater than or less than their respective means. Conversely, the correlation coefficient is negative if the variables lie on opposite sides of their respective means.

For example, the correlation coefficient for health index and sufficiency rating describes the linear dependence between these two variables. If the variables are correlated (i.e., their correlation coefficient is high), a predictive relationship between them can be inferred. On the other hand, if the correlation coefficient is small, no linear relationship exists.

Probability distribution describes the range of possible values that a variable can attain and the probability that the value of the variable is within any subset of that range. Probability distributions are computed using the average and standard deviation for a series of data points. The distributions in this section show possible values for measures such as sufficiency rating, health index, and IRI as well as the probability of certain values occurring. It is important to note that the probability distribution function assumes a normal (i.e., "bell shaped") distribution and does not take into account the fact that sufficiency rating and health index cannot exceed 100.

Cumulative distribution is another method of graphically representing the range of values that a variable can attain. Cumulative distributions also are computed using the average and the standard deviation. However, cumulative distributions run from 0 to 1 and, for any given value, represent the percentage of the total population having that value or less. This calculation also assumes a normal distribution of values and does not reflect the maximum value of 100 for sufficiency rating and health index.

Bridge Analysis

For the bridge data analysis, CS reviewed:

- Delaware data – 62 bridges with element data obtained from Pontis;
- Maryland data – 118 bridges with element data obtained from the Maryland bridge management system and 118 bridges without element data obtained from the Maryland National Bridge Inventory (NBI) file; and
- Virginia data – 385 bridges with element data obtained from Pontis.

CS did review a recent Pontis database for Washington, D.C. However, this database did not contain any structures on I-95. Therefore, bridges for the District of Columbia were not included in this analysis.

The bridge analysis focused on the following key data items, which are available from the NBI or may be calculated using Pontis:

- Deck Rating (NBI Element 58);
- Superstructure Rating (NBI Element 59);
- Substructure Rating (NBI Element 60);
- Sufficiency Rating (calculated);

- Health Index for deck elements only (calculated);
- Health Index for superstructure elements only (calculated);
- Health Index for substructure elements only (calculated); and
- Health Index for all elements.

Historically, the sufficiency rating and structurally deficient/functionally obsolete (SD/FO) values have been used as the measure of bridge condition. The development in recent years of the health index in Pontis provides a different measure of the structural condition of a bridge. It is important to note that health index does not attempt to measure the functional adequacy of a bridge.

Discussion of Current Measures

Although states are able to calculate sufficiency rating for themselves, the official calculation is performed by FHWA using NBI data submitted annually by states. The sufficiency rating uses four separate factors to obtain a numeric value that indicates whether a bridge is sufficient to remain in service. The result is a percentage in which 100 percent represents an entirely sufficient bridge and zero percent represents an entirely insufficient or deficient bridge. The sufficiency rating is never less than 0 or more than 100.

A bridge's sufficiency rating affects its eligibility for Federal funding for maintenance, rehabilitation, or replacement activities. For bridges to qualify for Federal replacement funds, they must have a rating of 50 or less. To qualify for Federal rehabilitation funding, a bridge must have a sufficiency rating of 80 or less.

The sufficiency rating factors are:

1. S1, the structural adequacy and safety factor;
2. S2, the serviceability and functional obsolescence factor;
3. S3, the essentiality for public use factor; and
4. S4, the special reductions factor.

S1 is a function of the lowest rating code of Item 59 (Superstructure Rating), Item 60 (Substructure Rating) or Item 62 (Culvert Rating), and Item 66 (Inventory Rating).

S2 is a function of Item 58 (Deck Rating), Item 67 (Structural Evaluation), Item 68 (Deck Geometry), Item 69 (Underclearances), Item 71 (Waterway Adequacy), Item 72 (Approach and Road Alignment), Item 29 (ADT), Item 51 (Bridge Roadway Width), Item 28 (Lanes on the Structure), Item 100 (Defense Highway), Item 32 (Approach Roadway Width), Item 43 (Structure Type), and Item 53 (Vertical Clearance Over Deck).

S3 is a function of S1, S2, Item 29 (ADT), Item 100 (Defense Highway), and Item 19 (Detour Length).

To obtain the sufficiency rating, S4 is subtracted from the sum of S1, S2, and S3. S4 is only used when the sum of S1, S2, and S3 is greater or equal to 50. S4 is a function of Item 19 (Detour Length), Item 36 (Traffic Safety Features), and Item 43 (Structure Type).

Similar to sufficiency rating, health index provides a single numeric indicator of the structural health of the bridge. This indicator is expressed as a percentage from zero, which corresponds to the worst possible condition, to 100, which is the best condition. Health index is a function of the fractional distribution of the bridge element quantities across the range of their applicable condition states. Concretely, the health index value of an entire bridge is calculated as a weighted average of the health indexes of its elements, where elements are weighted by their total quantity and relative importance (i.e., failure cost). Consequently, the bridge health index is a function of the failure cost of each element of the bridge, quantity of each element on the bridge, and condition state of each element. Likewise, the health index of each element is a function of its unit failure cost, its quantity on the bridge, and its condition state on the bridge.

Though the sufficiency rating provides a consistent standard for the evaluation of sufficiency to remain in service, it is not comprehensive enough to provide performance-based information on each element of the bridge. For example:

- Sufficiency rating focuses on the overall condition of the bridge, making it irrelevant for maintenance decision-making.
- Sufficiency rating emphasizes the functionality and geometric characteristics of the bridge rather than an element-based view of the bridge. (Factor S2)
- Sufficiency rating assumes that the worst distress between the superstructure, substructure, or culvert will represent the overall structural adequacy and safety of the bridge (Factor S1). This means sufficiency rating cannot account for localized problems or safety issues.
- The superstructure, substructure, and culvert ratings are on a 0-9 scale by severity of deterioration. These ratings do not give a picture of the deterioration process at work or the extent of deterioration.
- Sufficiency rating focuses only on the major parts of the bridge: superstructure, substructure, deck, and culverts. The lack of detail makes it impossible to estimate the cost of rehabilitation or maintenance.

On the other hand, the health index indicates the condition of each element at a given time. The bridge health index aggregates element-level health indexes where weights, which embody the economic consequences of failure, are assigned to each element. The main advantage of the health index is that it links the condition of bridge to the resources allocated. Consequently, decision-makers can evaluate the impact of several resource allocation scenarios on the future condition of a bridge network. Also, maintenance and rehabilitation decision-making is facilitated since the measures are detailed enough to represent localized problems.

Analysis of Current Measures

The first part of the analysis of bridge data involved the calculation of basic statistical information by state and across all states. These basic statistics, not weighted by bridge deck area, are presented in Table 4.1.

Table 4.1 Basic Bridge Statistics – Not Weighted

State	Statistic	Deck Rating	Superstructure Rating	Substructure Rating	Sufficiency Rating	Health Index – Deck	Health Index – Superstructure	Health Index – Substructure	Health Index – Overall
DE	Count	45	45	45	61	44	45	61	61
DE	Min	5	5	4	53	50	61	67.5	67.5
DE	Max	8	8	8	98	100	100	100	100
DE	Average	6.56	6.40	6.33	84.47	89.14	88.63	94.87	92.44
DE	Median	7	6	6	85	99.85	92.5	97.4	93.8
DE	Std Dev	0.66	0.65	0.77	10.46	14.65	10.70	7.46	6.44
DE	Variance	0.43	0.43	0.59	109.36	214.64	114.44	55.62	41.44
MD	Count	107	108	108	140	98	108	118	118
MD	Min	5	5	5	50.2	25	67	46.2	49.3
MD	Max	8	9	9	100	100	100	100	100
MD	Average	6.64	6.36	6.19	81.20	84.44	96.63	90.18	88.96
MD	Median	7	6	6	83.60	75	99.7	94.35	93.05
MD	Std Dev	0.62	0.81	0.78	10.10	17.03	6.56	11.39	11.51
MD	Variance	0.38	0.66	0.61	102.02	290.15	43.01	129.78	132.41
VA	Count	223	223	223	373	220	222	370	372
VA	Min	4	4	4	25.3	25	48.3	12.8	24.4
VA	Max	9	9	9	100	100	100	100	100
VA	Average	6.57	6.57	6.28	81.97	87.54	92.39	89.77	89.69
VA	Median	7	7	6	83	100	97.8	95.3	94.2
VA	Std Dev	0.94	1.08	1.07	12.52	15.13	11.38	12.75	11.56
VA	Variance	0.88	1.16	1.14	156.78	228.79	129.59	162.65	133.53
ALL	Count	375	376	376	574	362	375	549	551
ALL	Min	4	4	4	25.3	25	48.3	12.8	24.4
ALL	Max	9	9	9	100	100	100	100	100
ALL	Average	6.59	6.49	6.26	82.05	86.89	93.16	90.42	89.84
ALL	Median	7	6	6	83.00	100	98	95.5	94
ALL	Std Dev	0.83	0.97	0.96	11.78	15.65	10.42	12.08	11.12
ALL	Variance	0.68	0.93	0.92	138.79	244.83	108.64	145.82	123.69

The following are some observations regarding the basic statistics:

- Counts only include assets where the measure is not missing. Differences in the counts can be attributed primarily to the absence of certain types of elements. For example, culverts generally do not have deck elements and, therefore, would not have either a deck rating or deck health index.
- The low standard deviation and variance for the NBI ratings compared to the equivalent health index measures can be attributed to the small number of values the NBI rating can hold. For these statistics, only ratings from zero to nine were considered.
- The combined statistics for all states do not vary dramatically from the statistics for any individual state. The ratings and the component-based health indexes for Virginia vary more than in the other states. There is no reason to attribute this to anything other than actual variability in the condition of the corresponding structures.

Table 4.2 presents some of the same basic statistics, except that values have been weighted by bridge deck area. Deck area is one of the primary metrics by which bridges generally are categorized. Only the statistics necessary to support calculations of probably and cumulative distributions were calculated.

Table 4.2 Basic Bridge Statistics – Weighted

State	Statistic	Deck Rating	Superstructure Rating	Substructure Rating	Sufficiency Rating	Health Index – Deck	Health Index – Superstructure	Health Index – Substructure	Health Index – Overall
DE	Count	45	45	45	61	44	45	61	61
DE	Average	6.20	6.03	6.63	78.45	78.87	94.91	95.31	88.96
DE	Std Dev	0.62	0.68	0.75	7.81	11.93	8.36	8.14	5.05
DE	Variance	0.38	0.46	0.57	61.07	142.31	69.89	66.32	25.55
MD	Count	107	108	108	113	98	103	103	103
MD	Average	6.61	6.40	6.14	79.66	82.36	95.70	92.23	90.55
MD	Std Dev	0.53	0.65	0.69	8.55	17.99	7.56	9.53	9.76
MD	Variance	0.28	0.42	0.48	73.17	323.57	57.14	90.80	95.19
VA	Count	213	213	213	215	211	211	212	212
VA	Average	6.81	6.73	6.62	81.47	88.42	93.79	89.94	90.58
VA	Std Dev	1.12	1.38	1.30	12.82	14.63	10.26	12.14	9.89
VA	Variance	1.25	1.91	1.70	164.34	213.93	105.29	147.42	97.78
ALL	Count	365	366	366	389	353	359	376	376
ALL	Average	6.61	6.46	6.39	80.21	84.75	94.48	91.81	90.16
ALL	Std Dev	0.80	0.98	0.96	10.37	14.76	9.25	10.68	8.85
ALL	Variance	0.64	0.96	0.93	107.49	217.85	85.57	114.03	78.35

The following are some observations regarding the weighted statistics:

- The count of assets goes down in many cases because bridges without a deck area (e.g., culverts) are removed from the results.
- Some of the other statistics (e.g., average, standard deviation, and variance) are reduced when weighted by deck area. This reflects both the smaller set of assets being considered as well as a general trend observed in other states that health index weighted by deck area is lower than the average health index.[1]
- Despite the differences observed, the statistics generally are very close for bridges that have and have not been weighted by deck area. For the data covered by this analysis, this indicates that the values are well distributed across the spectrum of possible results.

For the second phase of the analysis, CS measured the correlation between different measures. The closer the correlation coefficient is to 1 or -1, the greater the statistical relationship between two sets of values. It is important to note that the correlation coefficient does not make any determination regarding accuracy of the values nor does it infer any cause/effect relationship between the values. Table 4.3 presents the correlation coefficients for bridge measures within individual states and across all states.

Table 4.3 Bridge Correlation Coefficients

State	Statistic	Superstructure Rating	Substructure Rating	Sufficiency Rating	Health Index – Deck	Health Index – Superstructure	Health Index – Substructure	Health Index – Overall
DE	Deck Rating	0.05	0.39	0.47	0.62	0.08	0.23	0.60
DE	Superstructure Rating		0.09	0.13	0.05	0.43	-0.03	-0.03
DE	Substructure Rating			0.51	0.20	-0.12	0.67	0.37
DE	Sufficiency Rating				0.37	0.32	0.38	0.25
DE	Health Index – Deck					0.12	0.20	0.60
DE	Health Index – Superstructure						-0.11	0.63
DE	Health Index – Substructure							0.67
MD	Deck Rating	0.51	0.38	0.16	0.48	0.18	-0.10	0.09
MD	Superstructure Rating		0.58	0.32	-0.03	-0.03	0.00	0.04
MD	Substructure Rating			0.52	0.17	-0.14	0.02	0.45

[1] *2008-2011 Draft Statewide Transportation Improvement Program: Evaluation of the State Bridge Program*, Oregon Department of Transportation, Bridge Engineering Section, April 2007.

State	Statistic	Superstructure Rating	Substructure Rating	Sufficiency Rating	Health Index – Deck	Health Index – Superstructure	Health Index – Substructure	Health Index – Overall
MD	Sufficiency Rating				0.13	-0.19	0.04	0.43
MD	Health Index – Deck					0.26	0.31	0.36
MD	Health Index – Superstructure						0.27	0.33
MD	Health Index – Substructure							0.99
VA	Deck Rating	0.74	0.70	0.40	0.59	0.54	0.49	0.35
VA	Superstructure Rating		0.69	0.47	0.47	0.52	0.36	0.25
VA	Substructure Rating			0.41	0.47	0.47	0.62	0.28
VA	Sufficiency Rating				0.67	0.68	0.64	0.29
VA	Health Index – Deck					0.38	0.32	0.74
VA	Health Index – Superstructure						0.39	0.77
VA	Health Index – Substructure							0.84
ALL	Deck Rating	0.65	0.62	0.36	0.58	0.45	0.43	0.36
ALL	Superstructure Rating		0.63	0.41	0.38	0.46	0.29	0.18
ALL	Substructure Rating			0.44	0.43	0.38	0.60	0.31
ALL	Sufficiency Rating				0.62	0.60	0.60	0.30
ALL	Health Index – Deck					0.28	0.30	0.59
ALL	Health Index – Superstructure						0.30	0.62
ALL	Health Index – Substructure							0.86

The following are some observations regarding the correlation coefficients:

- There are no firm rules regarding how close a coefficient must be to 1 or -1 in order to be considered significant. For purposes of this analysis, CS has chosen 0.70 as a reasonable threshold to identify values that are well correlated. Values of 0.70 or greater have been highlighted in Table 4.3.
- Theoretically, both sufficiency rating and overall health index represent the structural condition of a bridge. If these measures were equally good for this purpose, we would expect a relatively high correlation between these values. However, as shown in Table 4.3, the correlation coefficients are DE=0.25, MD=0.43, VA=0.29, and ALL=0.30. At least part of this difference can be explained by the fact that the sufficiency rating is a combination of structural

adequacy (55 percent), serviceability (30 percent), and essentiality (15 percent).[2]

- The same reasoning applies to Deck Rating versus Health Index – Deck, Superstructure Rating versus Health Index – Superstructure, and Substructure Rating versus Health Index – Substructure. Some of these component values are significantly better correlated than the overall measures. For example, in Delaware the correlations of the deck and substructure measures are 0.62 and 0.67, respectively. These relatively high correlations indicate that the NBI ratings can be reasonable component-based measures of condition once the nonstructural aspects of the sufficiency rating calculation are removed.
- However, some component-based correlations are much worse than the overall measures. For example, in Maryland, the superstructure and substructure measures are -0.03 and 0.02, respectively. This may indicate a systemic problem with the way in which inspectors capture either element-level data or NBI ratings. CS is aware of similar issues in other states, who report that the FHWA NBI Translator built into Pontis, which calculates NBI ratings from element data, is giving significantly different values than the NBI ratings entered by inspectors.
- The highlighted values in Table 4.3 are associated with correlations of the Health Index to subcomponents of the Health Index or one NBI rating with another. They are not associated with correlations of Health Index and NBI values. The highest correlations between Health Index and NBI are found for the substructure ratings in Delaware and Virginia.

In addition to computing the correlation coefficients, CS also prepared probability and cumulative distributions and associated graphs. A large number of graphs were produced and representative samples are shown below. Figure 4.1 shows probability distributions across all states for Health Index – Overall, Health Index – Deck, Sufficiency Rating, and Deck Rating. The graphs for other measures and individual states generally are not significantly different.

The similarity between Health Index – Overall and Sufficiency Rating graphs reflects the modest differences in the mean and variance for these measures. The exception is Health Index – Overall for Delaware. A significantly lower variance resulted in a narrower distribution. This trend is demonstrated by the extremely sharp curve for Deck Rating. This graph, which repeats for the other NBI ratings, is driven by the small number of values that an individual rating can assume and the correspondingly lower variance for this measure.

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[2] *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges*, FHWA-PD-96-001, December 1995.

Figure 4.1 Bridge Probability Distributions – All States

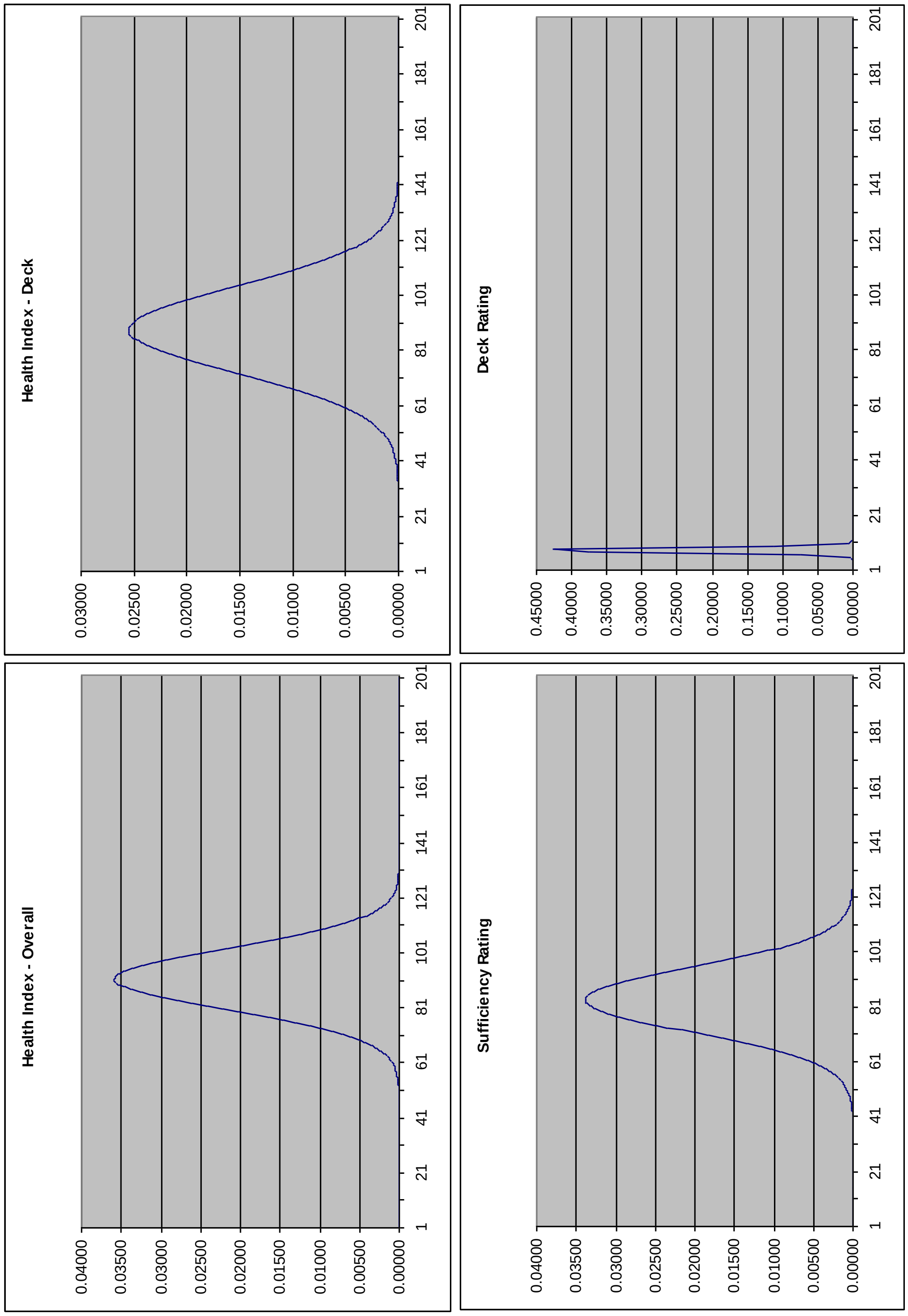
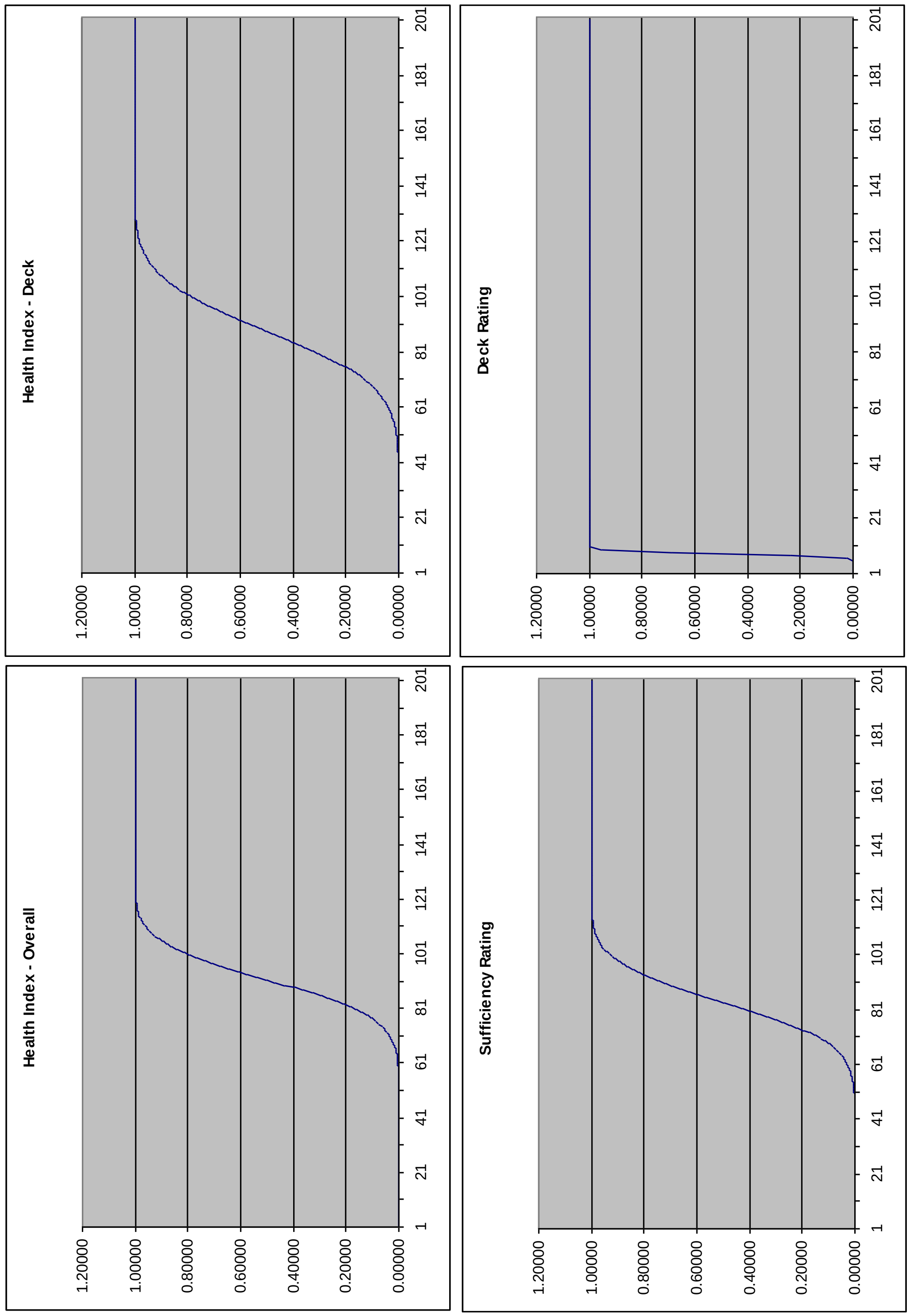


Figure 4.2 shows cumulative distributions across all states for Health Index – Overall, Health Index – Deck, Sufficiency Rating, and Deck Rating. The graphs for other measures and individual states generally are not significantly different.

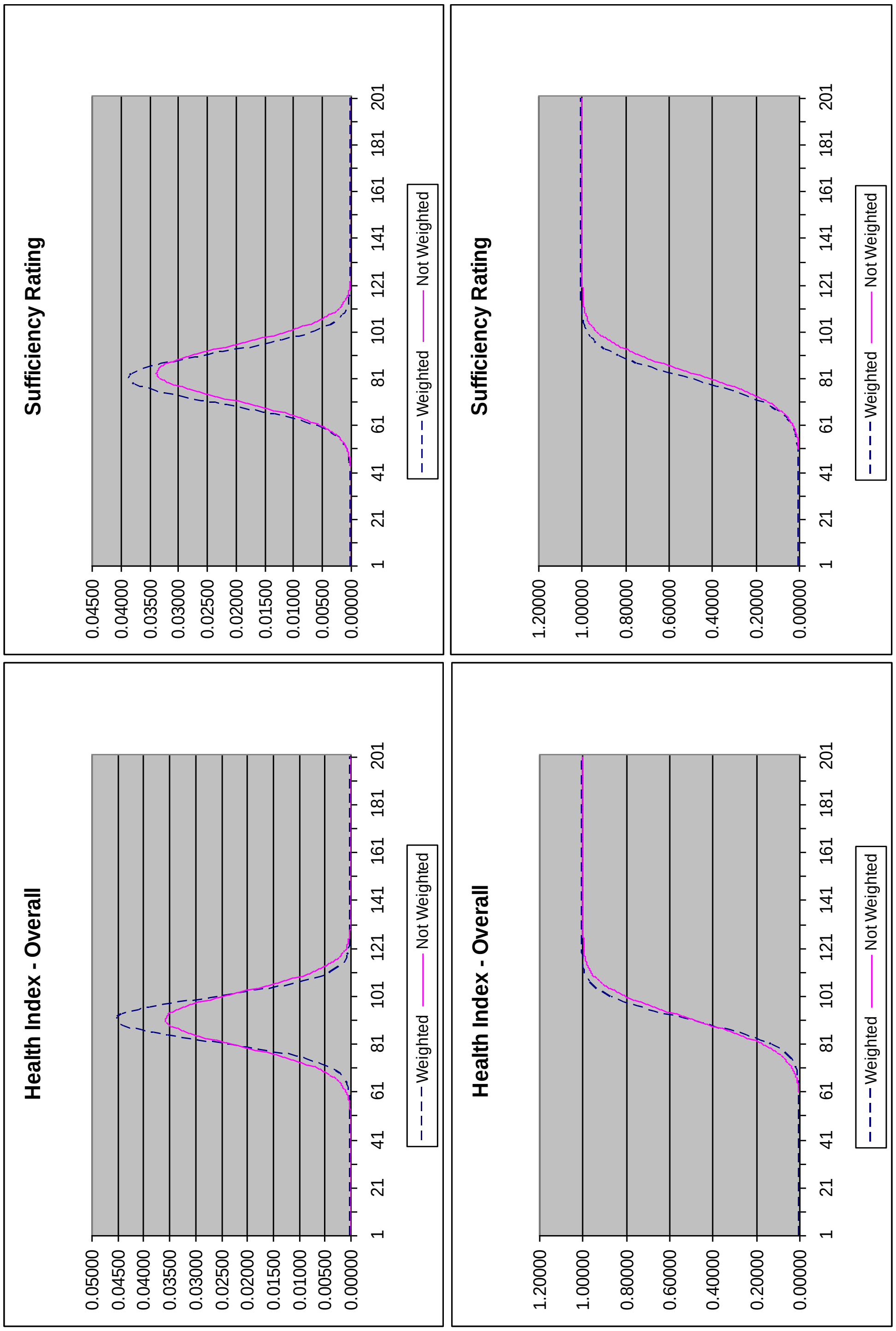
Again, the sharp curve for Deck Rating reflects the small number of values and correspondingly small variance for this measure.

Figure 4.2 Bridge Cumulative Distributions – All States



Figures 4.1 and 4.2 show values not weighted by deck area. Figure 4.3 shows Health Index – Overall and Sufficiency Rating comparing values that are weighted and not weighted.

Figure 4.3 Weighted Bridge Distributions – All States



Generally, the weighted measures are sharper (i.e., the probability distributions are narrower and the peaks higher). This reflects the fact that fewer assets are included in the calculations because bridges without deck areas are not included. Otherwise, the curves are very similar, which reinforces conclusions associated with Table 4.2.

Pavement Analysis

For the pavement data analysis, CS reviewed:

- Delaware data – 193 segments on I-95 totaling approximately 37 miles;
- Maryland data – 2,179 segments on I-95 totaling approximately 217 miles; and
- Virginia data – 192 segments on I-95 totaling approximately 371 miles.

Note that these mileage totals generally do not match the official number of I-95 miles by state.[3] The totals reported above were calculated by summing the difference of beginning and ending mile points for each segment. For Maryland and Virginia, the data include separate records for northbound and southbound roadways. The data for Delaware appear to cover one direction only. Also, although CS originally believed that Maryland did not provide data for the section of I-95 that lies with the city limits of Baltimore, a more thorough review of the data determined that these records were present but there was a mismatch between county name and county code. CS corrected these data and matched the records to the correct road section.

The pavement analysis focused on the following key data elements:

- International Roughness Index (IRI), which was provided by all states;
- Overall Pavement Condition (OPC), which was reported by Delaware and calculated for Virginia by CS;
- Critical Condition Index (CCI), which was reported by Virginia; and
- Other distress index data (e.g., cracking, rutting, etc.) as appropriate.

Historically, IRI has been used as the measure of pavement condition while Present Serviceability Rating (PSR) has measured the ability of the pavement to service expected traffic. These values are provided by states as part of their annual Highway Performance Monitoring System (HPMS) report. Changes to the HPMS reporting process are part of FHWA's HPMS Reassessment 2010+ initiative. These changes include improving the consistency IRI measurement and reporting as well as submitting more data elements (e.g., rutting, faulting, cracking, overlay information).

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[3] http://en.wikipedia.org/wiki/Interstate_95.

Discussion of Current Measures

Pavement roughness is defined in accordance with the American Society for Testing and Materials (ASTM) standard E867 as "the deviation of a surface from a true planar surface with characteristic dimensions that affect vehicle dynamics and ride quality." IRI was chosen by the World Bank in the 1980s to quantify roughness. After a detailed study of various methodologies and road profiling statistics, IRI was chosen as the HPMS standard reference roughness index. The HPMS data reporting unit for IRI is meters/kilometer (inches/mile).

IRI is the amount of roughness in a measured longitudinal profile. Lower values for IRI indicate smoother pavement. IRI is based on average rectified slope (ARS), which is a filtered ratio of a standard vehicle's accumulated suspension motion (e.g., millimeters or inches) divided by the distance traveled by the vehicle during the measurement. IRI is equal to ARS multiplied by 1,000. IRI is computed from a single longitudinal profile measured with a road profiler in both the inside and outside wheel paths of the pavement. The average of these two IRI measurements is reported as the roughness of the pavement section.

However, IRI only captures road smoothness. Some states use other indicators, such as OPC or CCI, to describe the general health of the pavement. Indeed, the pavement may be very smooth and yet have deep rutting in the wheel path or cracking that allows water to enter and cause deterioration. OPC and CCI both are composite values that combine several distress ratings to produce an overall pavement condition measure.

Delaware uses the following process to calculate OPC for asphalt pavement:

- Convert five distress measures into numeric indexes using the tables shown in Figure 4.4;

Figure 4.4 Delaware Pavement Distress Conversation Tables

Asphalt Patching

		Extent		
	100	Low	Med	High
Severity	Low	92	84	70
	Med	80	58	40
	High	72	46	20

Surface Defects

		Extent		
	100	Low	Med	High
Severity	Low	92	86	80
	Med	86	74	64
	High	80	66	52

Fatigue Cracking

		Extent		
	100	Low	Med	High
Severity	Low	92	84	70
	Med	80	58	40
	High	72	46	20

Block Cracking

		Extent		
	100	Low	Med	High
Severity	Low	88	80	68
	Med	82	68	56
	High	74	50	40

TransCrack

		Extent		
	100	Low	Med	High
Severity	Low	88	78	68
	Med	84	72	58
	High	76	50	40

- Calculate the average (avg) and the standard deviation (stdev) of the five numeric indexes; and
- Calculate OPC using the formula OPC = avg – (1.25 * stdev).

Generally, OPC is a number between 0 and 100. In some cases, OPC is divided by 20 and reported as a number between 0 and 5.

Virginia uses the following process[4] to calculate CCI for asphalt pavement:

- Calculate a load distress index (LDR) to describe distresses related to wheel loads (e.g., alligator cracking, delaminations, patching, potholes and rutting);
- Calculate a nonload distress index (NDR) to describe distresses related to weathering (e.g., bleeding, block cracking, linear cracking and reflection cracking); and
- Define CCI as the lower of the LDR and NDR index values.

Both LDR and NDR start at a base value of 100. Points are deducted based on the severity and frequency of occurrence of each distress. Some distresses are classified as more detrimental to pavement and are weighted more heavily. The deductions are based on the deduct curves in the PAVER pavement management system. The specifics of these calculations are beyond the scope of this document but are available from the Virginia Department of Transportation. Like OPC, CCI is a number between 0 and 100. Note that IRI is not one of the inputs into the CCI calculation.

Analysis of Current Measures

As with bridges, the first part of the pavement analysis involved the calculation of basic statistical information by state and across all states. These basic statistics, not weighted by pavement segment length, are presented in Tables 4.4 and 4.5.

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[4] McGhee, K. H., *Development and Implementation of Pavement Condition Indices for the Virginia Department of Transportation, Phase 1: Flexible Pavement*, Virginia Department of Transportation, Maintenance Division, September 2002.

Table 4.4 Basic Pavement Statistics Part 1 – Not Weighted

State	Statistic	IRI – Left	IRI – Right	IRI – Average	Transverse Cracks – Severity 1 (linear feet)	Transverse Cracks – Severity 2 (linear feet)	Longitudinal Cracks – Severity 1 (linear feet)	Longitudinal Cracks – Severity 2 (linear feet)	Alligator Cracks – Severity 1 (square feet)	Alligator Cracks – Severity 2 (square feet)	Alligator Cracks – Severity 3 (square feet)
DE	Count	91	91	91							
DE	Min	49	49	49							
DE	Max	368	354	358							
DE	Average	144	156	151							
DE	Median	122	135	138							
DE	Std Dev	76	80	74							
DE	Variance	5731	6334	5458							
MD	Count			2179							
MD	Min			31							
MD	Max			482							
MD	Average			83							
MD	Median			67							
MD	Std Dev			47							
MD	Variance			2182							
VA	Count	192	192	192	192	192	192	192	192	192	192
VA	Min	44	41	45	0	0	0	0	0	0	0
VA	Max	160	181	160	12589	9767	5918	9010	15866	31659	10407
VA	Average	86	90	88	746	299	180	222	1284	1793	368
VA	Median	86	88	88	12	1	0	0	416	414	15
VA	Std Dev	21	23	21	N/A	N/A	N/A	N/A	N/A	N/A	N/A
VA	Variance	436	523	446	N/A	N/A	N/A	N/A	N/A	N/A	N/A
ALL	Count			2462							
ALL	Min			31							
ALL	Max			482							
ALL	Average			86							
ALL	Median			70							
ALL	Std Dev			48							
ALL	Variance			2330							

Table 4.5 Basic Pavement Statistics Part 2 – Not Weighted

State	Statistic	Patching – Wheel Path (square feet)	Patching – Non-wheel Path (square feet)	Number of Potholes	Rut Depth	CCI	OPC	IRI Condition Index	Rut Count	Rut Condition Index	Friction Number	Friction Condition Index	Cracking Index	Cracking Condition Index
DE	Count						193							
DE	Min						28							
DE	Max						100							
DE	Average						71							
DE	Median						71							
DE	Std Dev						15							
DE	Variance						225							
MD	Count				2179			2179	2179	2179	398	398	1956	1956
MD	Min				0.05			1	0	1	10	1	55	1
MD	Max				0.37			5	48	3	63	3	100	4
MD	Average				0.16			1.95	5	1.28	45	2.81	95	1.18
MD	Median				0.14			2	0	1	46	3	98	1
MD	Std Dev				0.07			0.96	11	0.66	6	0.47	7	0.51
MD	Variance				0.00			0.92	124	0.44	35	0.22	43	0.26
VA	Count	192	192	192	192	190								
VA	Min	0	0	0	0.1	16								
VA	Max	9190	11858	3	0.48	100								
VA	Average	411	393	0.08	0.19	73								
VA	Median	17	16	0	0.19	77								
VA	Std Dev	N/A	N/A	0.41	0.06	20								
VA	Variance	N/A	N/A	0.17	0.00	384								
ALL	Count													
ALL	Min													
ALL	Max													
ALL	Average													
ALL	Median													
ALL	Std Dev													
ALL	Variance													

The following are some observations regarding the basic statistics:

- In order to manage the size of Tables 4.4 and 4.5, some of the data from Virginia are not displayed. These values, which include lane joints, bleeding, and delaminations, are not significantly different than the values that are shown.
- Counts only include segments where the measure is not missing. It is interesting to note that IRI was not provided for all Delaware segments. Delaware only recently has begun to collect IRI for all pavement segments. Previously, Delaware only collected IRI for HPMS segments.
- In some cases, the standard deviation and the variance are very high. In fact, for the cracking measures in Virginia, these values were too high to be credible and were replaced with "N/A". Even without the standard deviation, a review of the minimum, maximum, average, and median values for these measures provides a sense of the variability. CS does not attach any particular significance to this except to note that variability in condition is expected in different road sections across a state the size of Virginia.
- IRI is the only common measure reported by all states. Generally, these measures show a reasonable uniformity across states. The numbers also correspond well when comparing any one state with the values for all states. This can be attributed to:
  - A reasonable level of uniformity in the conditions along I-95; and
  - A high degree of standardization in how IRI is measured, driven by the length of time this value has been used.

  It is interesting to note that Virginia does have a lower standard deviation and variance than the other states. These differences point to a higher level of uniformity in Virginia pavement condition.

Table 4.6 presents some of the same basic statistics, except that values have been weighted by segment length. Only the key measures are reported and only the statistics necessary to support calculations of probability and cumulative distributions were calculated.

Table 4.6 Basic Pavement Statistics – Weighted

State	Statistic	IRI – Average	OPC	CCI
DE	Count	91	193	
DE	Average	125.11	67.29	
DE	Std Dev	81.85	15.82	
DE	Variance	6699.20	250.27	
MD	Count	2177		
MD	Average	82.71		
MD	Std Dev	46.68		
MD	Variance	2179.25		
VA	Count	192		190
VA	Average	83.95		74.17
VA	Std Dev	21.57		19.81
VA	Variance	465.18		392.41
ALL	Count	2459		
ALL	Average	84.69		
ALL	Std Dev	35.46		
ALL	Variance	1257.41		

The following are some observations regarding the weighted statistics:

- For Maryland, the count dropped by two because there are two segments with a length of zero. This appears to be a result of the fact that Maryland records values for fixed-length segments (0.1 miles) and resets the mileposts at county boundaries. There are two records where the beginning and ending mileposts have the same value and fall at the edge of a county, which leads us to believe that the ending milepost is rounding down to the same value as the beginning milepost.
- The only state that shows any significant difference between weighted and nonweighted statistics is Delaware. When weighted by pavement length, the average IRI in Delaware dropped by approximately 17 percent. CS believes that this difference, which is not reflected in the other states, may be tied to the fact that Delaware did not collect IRI for all segments. Potentially, the segments that Delaware reported for the HPMS were skewed toward shorter segments with higher IRI values.
- It is interesting to note that a difference similar to the one for IRI in Delaware is not observed when comparing weighted and nonweighted values for OPC in Delaware. This seems to support the idea that the Delaware HPMS segments are not indicative of the overall condition of Delaware roads.

For the second phase of the pavement analysis, CS measured the correlation between IRI and other condition measures. Table 4.7 presents correlations for Delaware. Table 4.8 shows correlations for Maryland. Table 4.9 presents correlations for Virginia. Because IRI was the only measure reported by all states, CS was unable to produce any correlations between states.

Table 4.7 Pavement Correlation Coefficients – Delaware

Statistic	IRI – Right	IRI – Average	OPC
IRI – Left	0.81	0.95	0.12
IRI – Right		0.95	0.14
IRI – Average			0.14

Table 4.8 Pavement Correlation Coefficients – Maryland

Statistic	Rut Depth	Rut Count	Friction Number	Cracking Index
IRI – Average	0.19	-0.02	-0.07	-0.19
Rut Depth		0.87	-0.14	-0.11
Rut Count			-0.03	-0.08
Friction Number				0.26

Table 4.9 Pavement Correlation Coefficients – Virginia

Statistic	IRI – Right	IRI – Average	LDR	NDR	CCI
IRI – Left	0.86	0.96	-0.40	-0.37	-0.44
IRI – Right		0.97	-0.39	-0.38	-0.42
IRI – Average			-0.41	-0.39	-0.45
LDR				0.72	0.94
NDR					0.88

The following are some observations regarding the correlation coefficients:

- There are no firm rules regarding how close a coefficient must be to 1 or -1 in order to be considered significant. For purposes of this analysis, CS has chosen 0.70 as a reasonable threshold to identify values that are well correlated. Values of 0.70 or greater have been highlighted in Tables 4.7, 4.8, and 4.9.
- The only values in any state that are well correlated are values that are directly related (e.g., IRI – Left, – Right, and – Average; Rut Count and Rut Depth; and LDR, NDR, and CCI).
- Correlations between IRI and a composite value like OPC or CCI are marginal, at best. This leads to the conclusion that IRI, by itself, is not a good measure of overall pavement condition.

- Correlations between any two random distresses (e.g., Rut Depth and Cracking Index) are low. This result is not surprising since there is no particular reason to assume that having a distress of one type on a road segment inevitably would lead to distresses of other types.
- Some of the correlations between IRI and other values are negative. This is not an issue but reflects that fact that a higher IRI value indicates a worse reading while higher values for some other measures may indicate better values (e.g., higher is better for LDR, NDR, and CCI).

In addition to computing the correlation coefficients, CS also prepared probability and cumulative distributions and associated graphs. A large number of graphs were produced and representative samples are shown below. Figure 4.5 shows probability and cumulative distributions for Delaware. Figure 4.6 shows distributions for Maryland. Figure 4.7 shows distributions for Virginia.

The distribution graphs for Delaware reflect the higher standard deviation and variance encountered for the Delaware IRI readings compared to the other states. For Maryland, the IRI Condition Index graphs show an index computed from the IRI data. The sharp curves reflect the fact that this index can assume values only between 1 and 5. Maryland also computes similar indexes, with similar distribution graphs, for the other condition measures. For Virginia, the similarity between the IRI and CCI graphs is driven by similarities in the averages and standard deviations for these measures. This would indicate that these values, although not well correlated, are related in some way. This would seem to be true even though IRI is not a component of CCI.

Graphs for other condition measures are similar. Most of the graphs for the cracking measures in Virginia are so spread out that they almost appear to be straight lines. This is a function of the extremely high standard deviations for these measures, which were noted above for Table 4.4.

Figure 4.5 Pavement Distributions – Delaware

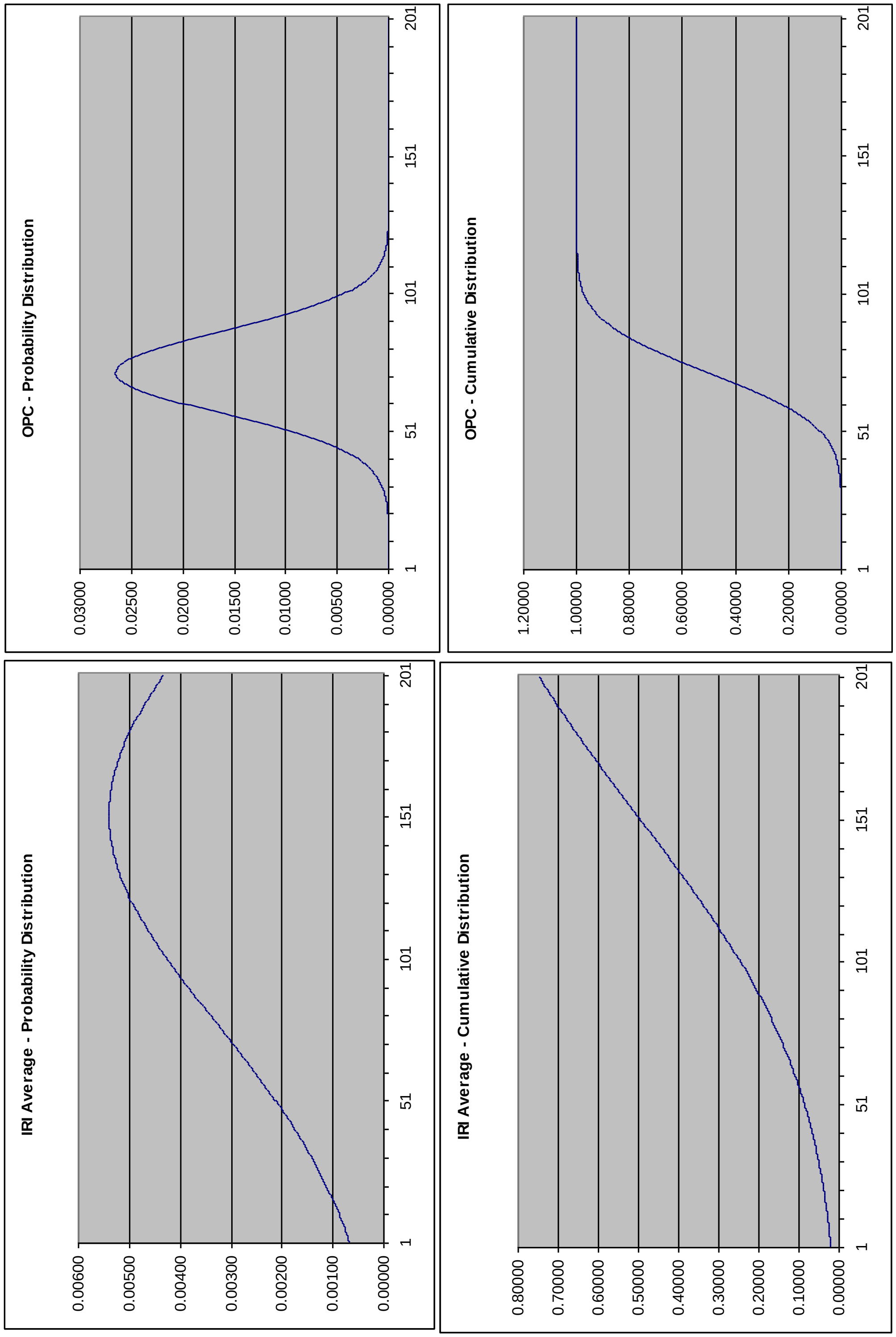


Figure 4.6 Pavement Distributions – Maryland

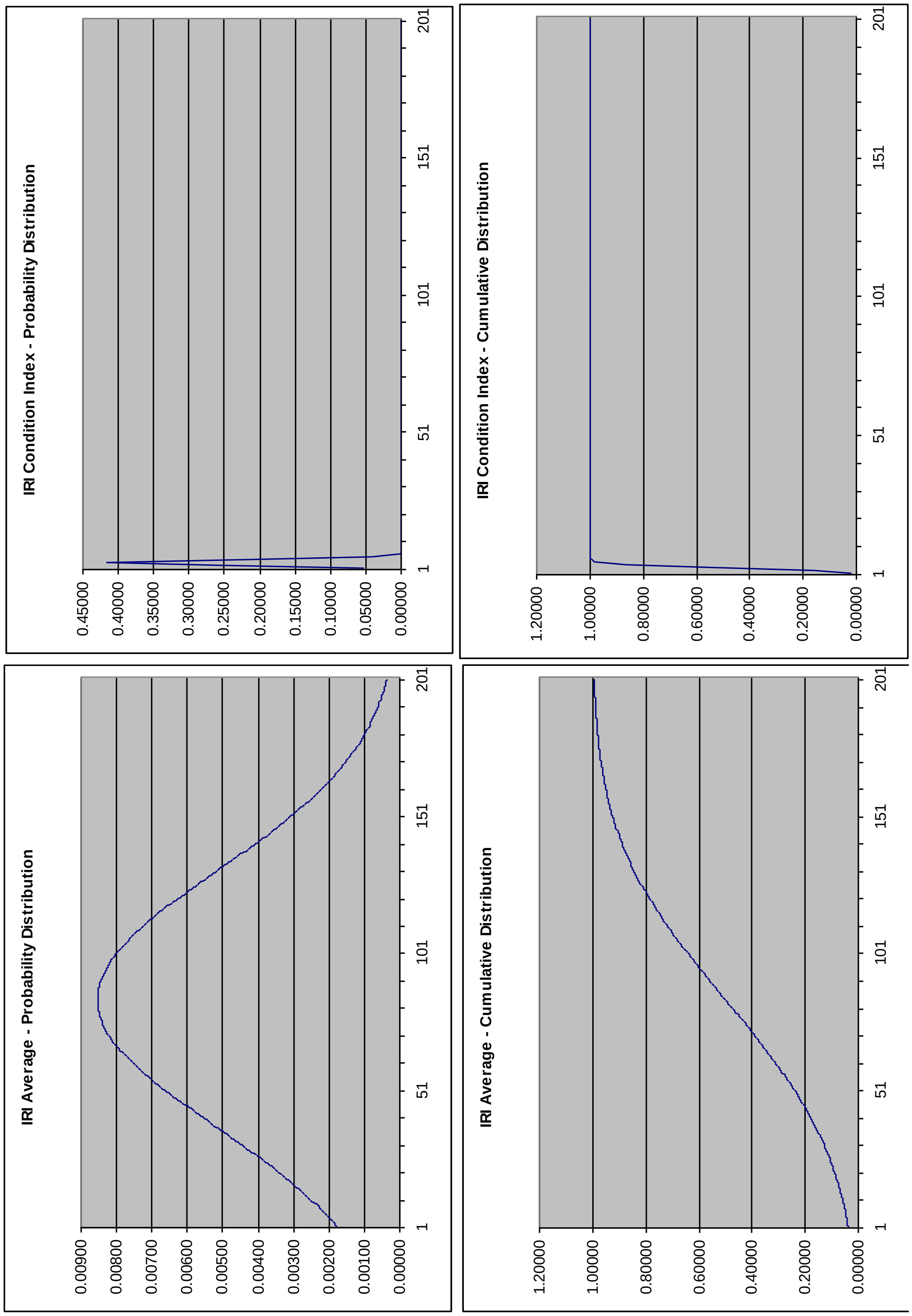
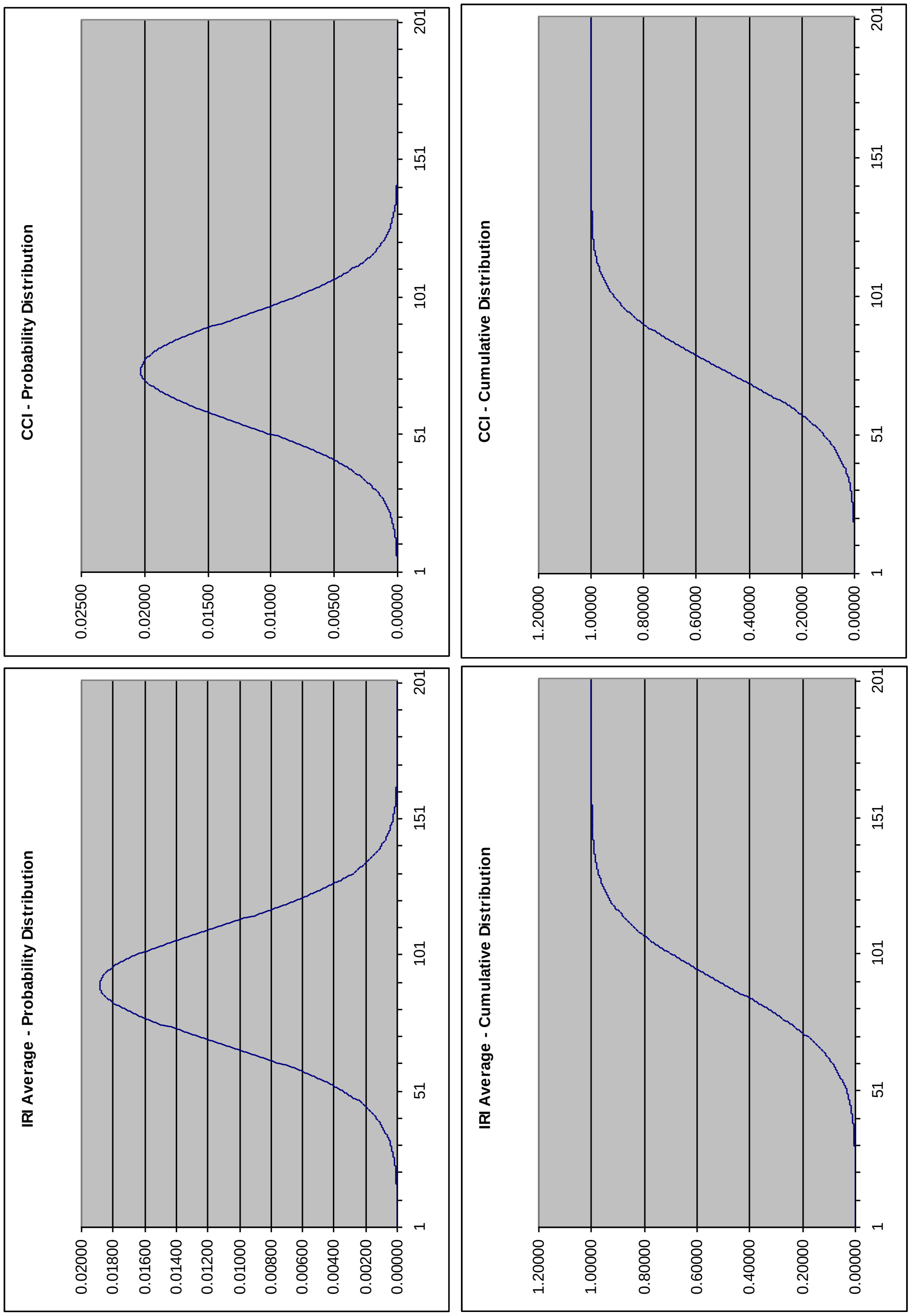
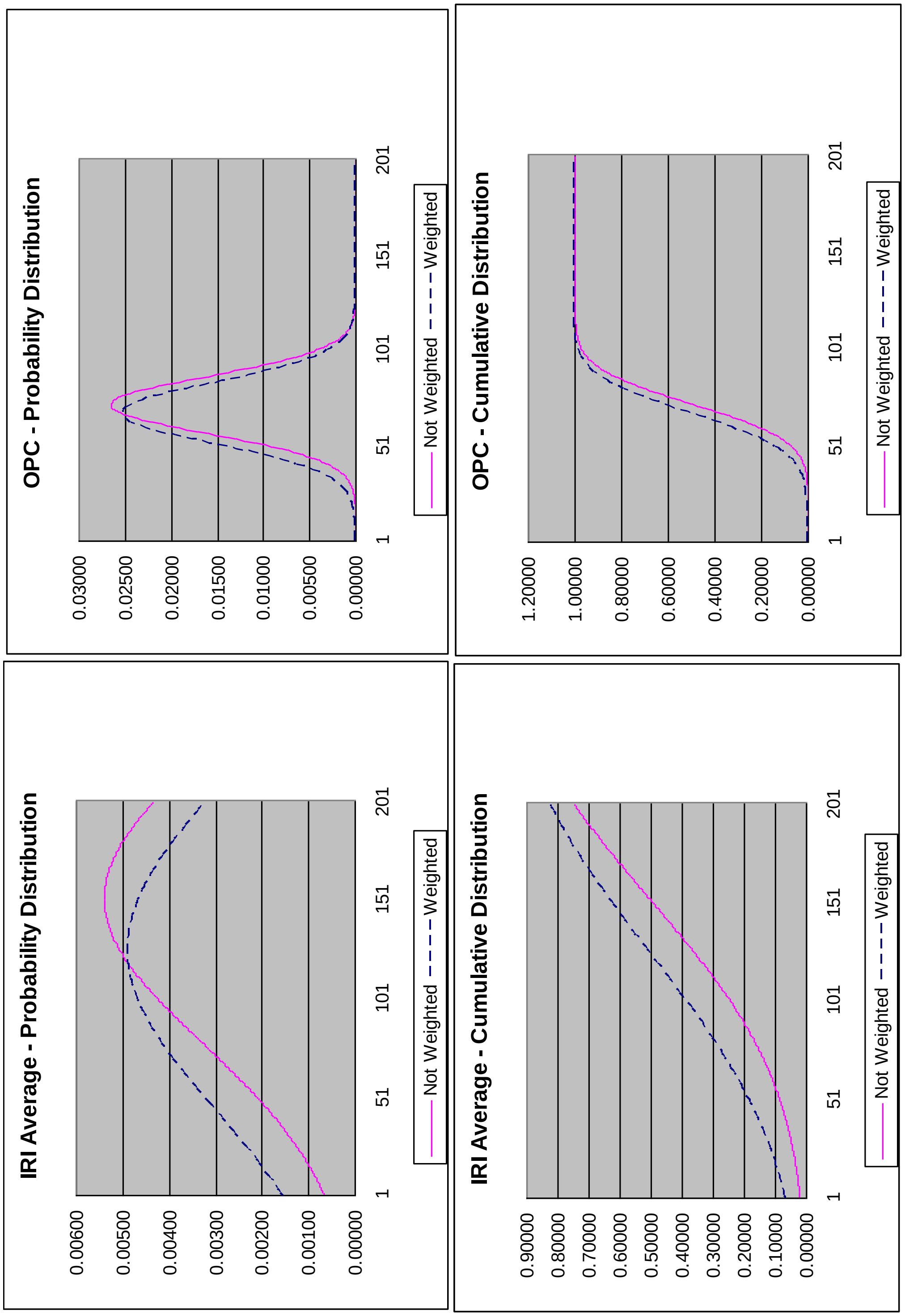


Figure 4.7 Pavement Distributions – Virginia



Figures 4.5, 4.6, and 4.7 show values not weighted by segment length. Figure 4.8 compares weighted and not weighted measures in Delaware.

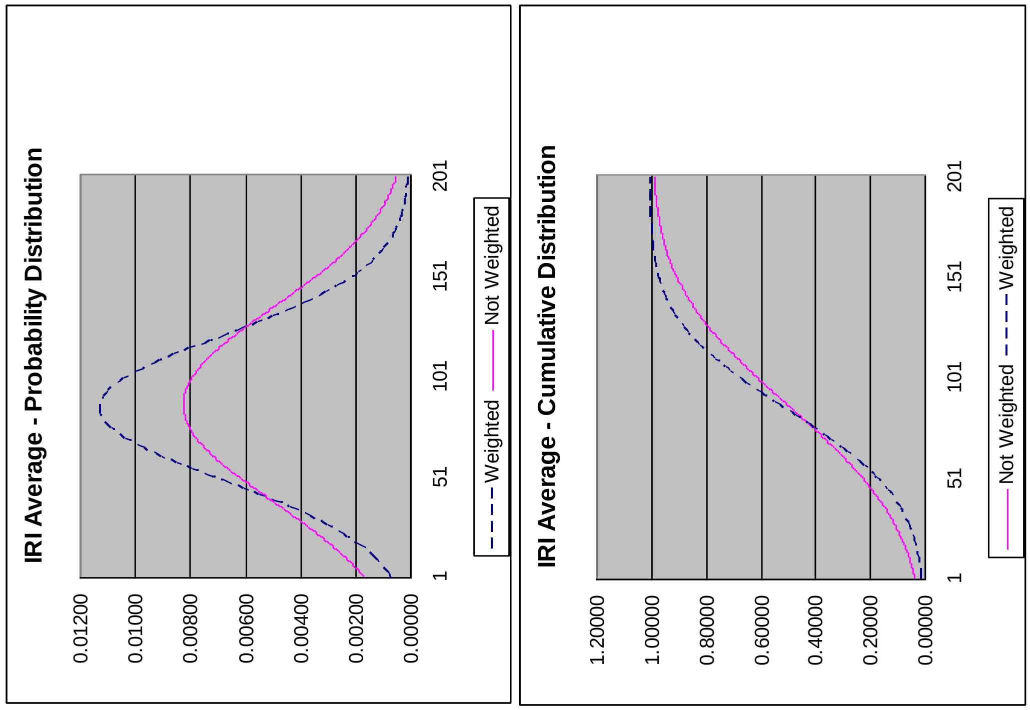
Figure 4.8 Weighted Pavement Distributions – Delaware



With the exception of Delaware, the distributions showing pavement measures that are weighted and not weighted by segment length are virtually identical.

Figure 4.9 compares the weighted and not weighted values for IRI across all states.

Figure 4.9 Pavement Distributions – All States



As with the bridge analysis, pavement measures weighted by segment length generally are sharper (i.e., the probability distributions are narrower and the peaks higher). For pavement, these differences are extremely small, which reinforces conclusions associated with Table 4.6.

Comparisons across States

A key piece of this analysis was focused on comparing algorithms for composite measures across states. Both Delaware and Virginia use composite measures. However, given the complexity of the Virginia algorithm for CCI, CS opted to focus on using the Delaware algorithm for OPC. Also, CS determined that the breadth of data elements provided by Maryland was insufficient to satisfy the requirements of the OPC algorithm. Therefore, CS concentrated on calculating OPC using Virginia data and the Delaware algorithm.

For this analysis, CS performed the following steps:

- Step 1 – Determine which Virginia data values match the Delaware distress measures used to calculate OPC.

  CS opted for the following mapping:

- VA Transverse Cracking (sum of all severities) = DE TransCrack;
- VA Longitudinal Cracking (sum of all severities) = DE Block Cracking;
- VA Alligator Cracking (sum of all severities) = DE Fatigue Cracking;
- VA Patching Area (wheel + nonwheel) = DE Asphalt Patching; and
- VA IRI * Rut Depth = DE Surface Defects.

Other Virginia measures such as lane joints, delaminations, bleeding, potholes, etc., were not used. The most problematic of these assumptions is IRI * Rut Depth = Surface Defects. However, CS assumed that any issues would be covered when an extent and severity for each measure are estimated in Steps 2 and 3. Also, as long as the calculations were performed consistently, CS believes that a meaningful correlation can be obtained regardless of the validity of the mapping.

- Step 2 – Convert the absolute quantities for each Virginia distress measure into a high, medium, or low extent required by the Delaware algorithm.

  CS attempted to convert the absolute quantities into percents scaled by the segment length. For each measure, the absolute values for all severities were added and then multiplied by the segment length in feet. The maximum value of this calculation was computed for each measure. Then, the measure for each segment was divided by the maximum. Percentages <= 33.3 were assigned a LOW extent. Percentages >= 66.7 were assigned a HIGH extent. All other values were assigned a MEDIUM extent.

- Step 3 – Convert the different severities for each Virginia distress measure into a high, medium, or low severity required by the Delaware algorithm.

  For each segment, CS assumed that the severity with the greatest absolute quantity of distress could be used as the overall severity level. For measures like alligator cracking, where Virginia already defined three severity levels, severity 1=LOW, severity 2=MEDIUM and severity 3=HIGH. For measures like transverse cracking, where Virginia only defined two severity levels, CS "created" an intermediate severity category equal to one-third of severity 1 plus one-third of severity 2. This left severities 1 and 2 with 66 percent of their original value. Again, the overall severity level for the segment was defined as the severity category with the greatest absolute value.

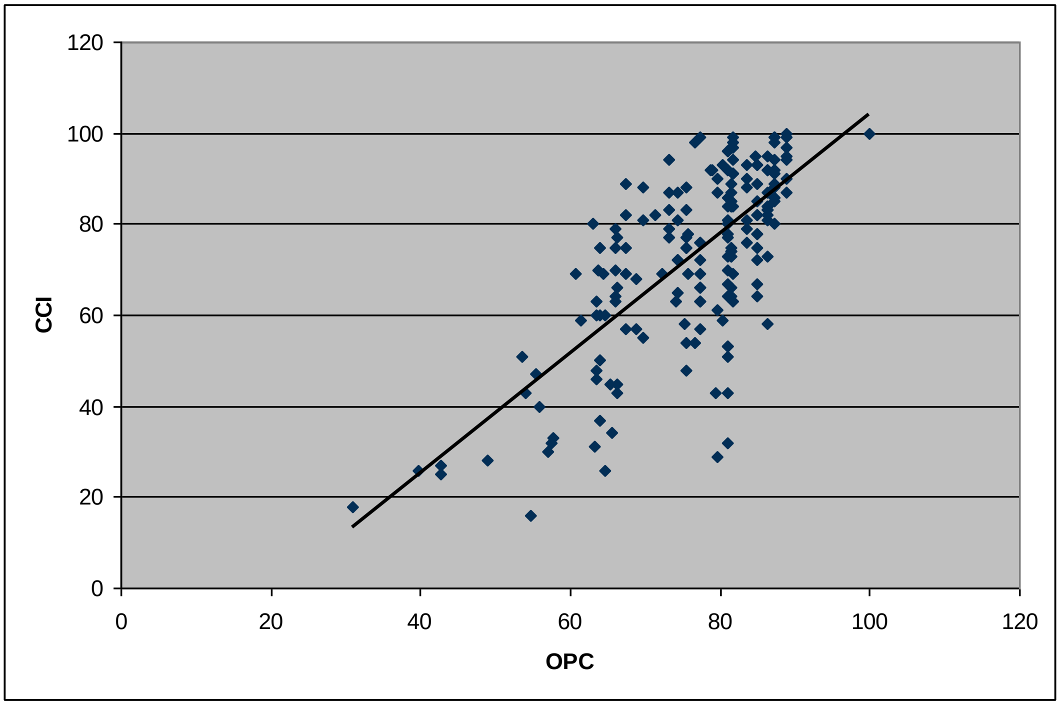
  For surface defects, CS observed that IRI * Rut Depth yielded values running approximately from 0 to 50. If this value was <= 16.67, then severity=LOW. If this value was >= 33.33, then the severity=HIGH. Otherwise, the severity=MEDIUM.

- Step 4 – Using the HIGH, MEDIUM, LOW severity and extent calculated in Steps 2 and 3 for each Virginia pavement segment, lookup five distress index values using the Delaware tables shown in Figure 4.4.

- Calculate OPC for each Virginia segment by calculating the average and standard deviation of the five distress index values and applying the formula OPC = avg – (1.25 * stdev).

The process described above produced an OPC value for 190 of the Virginia I-95 pavement records. OPC was not computed for two Virginia records where CCI was equal to -1. CS computed the correlation coefficient between the OPC and CCI values for the 190 Virginia pavement records. The coefficient is 0.714, which is sufficiently high to say that these values are reasonably well correlated. Recall that the correlation coefficient does not address the question of which value is more correct. CS believes that the Virginia calculation for CCI is more correct because it includes more data elements and does not rely on estimations of severity and extent. Figure 4.10 demonstrates the correlation between OPC and CCI in Virginia.

Figure 4.10 OPC versus CCI in Virginia



This exercise demonstrates that composite measures (i.e., measures that combine multiple distresses into a single value) tend to track well regardless of the algorithm used to produce the measure. And because neither OPC nor CCI correlate well with IRI in Virginia (OPC versus IRI=-0.49 and CCI versus IRI=-0.45), CS concludes that composite values provide a superior measure of pavement condition when compared to IRI.

4.2 DATA COLLECTION, VALIDATION, AND INTERPRETATION

In Task 1, CS contacted agencies responsible for the collection of bridge and pavement data for Delaware, Maryland, and Virginia. The data collection process is described in Section 2 and the specific individuals that provided the data are documented in Table 2.2.

As part of the data analysis task, CS again contacted these individuals to conduct follow-up interviews. The interviews focused on three main areas:

- The data collection process used by each state;
- How each state validates the quality of the data collected; and
- Standards adopted by each state for ranking asset condition.

This section documents the information received from each state.

Data Collection

States inspect and record information on the condition of bridges and pavement annually. This process supports both in-house uses (e.g., determination of maintenance priorities) as well as Federal reporting requirements for the NBI and the HPMS. While all states maintain engineers and other in-house bridge and pavement experts, CS observed that Delaware, Maryland, and Virginia all outsource at least some of their inspection activities.

Every state operates both a bridge management system (BMS) and a pavement management system (PMS) that, at a minimum, allow for storing and reporting of information. These systems also may provide capabilities to assist with inspection, calculate condition measures, and manage assets.

Delaware

For its bridges, Delaware uses a combination of in-house inspectors and outside consultants. The consultants are used primarily for specialized structures such as moveable bridges. Most inspectors take laptops equipped with the Pontis BMS into the field to record both NBI and element-level inspections. The bridge inspection engineers are responsible for ensuring that information is moved into the production Pontis database. This process usually occurs within one week following the inspection. The bridge inspection engineer is responsible for calculating the sufficiency rating at a later time (i.e., after the inspection has been moved into the production system and reviewed).

For its roads, Delaware previously collected pavement data using a windshield survey but recently has contracted with Applied Research Associates, Inc. (ARA), which will use an instrumented van to collect pavement measurements for future inspections. ARA will be responsible for calibrating the inspection tools. As part of the transition to ARA, Delaware has stated that they will begin measuring IRI on all road segments, not just those required for HPMS reporting. ARA will be responsible for moving all inspection data into the Delaware PMS, which also is provided by ARA. Although this process is expected to be highly automated, it is not clear what sort of time lag will be encountered since there is considerably more data (e.g., images and video logs) to be transferred.

Maryland

For its bridges, Maryland also uses a combination of in-house inspectors and outside consultants. The situation is identical to Delaware in that the consultants provide expertise on specialized structures (e.g., moveable and fracture critical bridges). NBI and element-level inspection information is captured on paper and entered into a custom BMS on a monthly basis. An outside consultant is used to calculate sufficiency rating for the bridges.

For its roads, Maryland uses its own equipment to automatically inspect approximately 11,000 lane-miles per year. Data are captured every 52 feet and rolled up to one-tenth-mile and one-half-mile values. Maryland contracts with ARA to compute values based on the inspection data, including condition indexes for IRI, cracking, friction, and rutting. On a weekly basis, data are transferred automatically to a custom PMS.

Virginia

For its bridges, Virginia also uses a combination of in-house inspectors and outside consultants. Consultants are used to compensate for insufficient in-house staff. These inspectors use a combination of paper forms and tablet-style laptops to perform both NBI and element-level inspections. Inspectors are responsible for transferring or entering data into the state's Pontis system on a weekly basis. A bridge safety engineer calculates the sufficiency rating for each bridge using the Pontis functionality.

For its roads, Virginia uses a contractor, Furgo Roadware, to perform automated inspections using an instrumented van. As with ARA in the other states, Furgo Roadware is responsible for calibrating the van and transferring the inspection information weekly into Virginia's Agile Assets PMS. This process is supported by dedicated information technology (IT) personnel.

Data Validation

Quality assurance (QA) involves validating the data, the data collection process, or both to ensure that the information being recorded is accurate. QA can include many types of tests, from looking for missing values to double-checking unexpected results to direct validation of some percentage of the original data. Frequently, the level of QA involves a tradeoff between the desired level of accuracy and the cost, in both time and money, to perform the tests.

Although states usually will provide guidelines for both bridge and pavement inspections, CS believes that bridge inspections rely more on the engineering expertise of the inspector than do pavement inspections. As discussed in the previous section, a pavement inspection primarily is an automated process that directly measures certain attributes of the road. There is a visual component to count/measure defects such as cracks and potholes, but overall the pavement inspection process is fairly mechanical.

The differences in the bridge and pavement inspection processes seem to affect the degree to which the data may be validated by a state. CS observed that the states participating in this study generally invest more effort in reviewing bridge data than pavement data. CS believes that this is a function both of the type of information gathered for pavement sections and the automated processes used to capture this information.

Delaware

For bridges, the bridge inspection engineer performs the initial QA check at the time data are transferred to the production Pontis database. This generally involves a visual review of the information being transferred. At this point, a team lead may review the information before sending it to a supervisor, who checks for missing data and invalid entries. Changes to inspection data happen infrequently, but if an error is discovered, the inspection engineer reviews the issue and makes any necessary changes before sending the change to the team lead for signoff.

For roads, a supervisor reviews the inspection data both before and after they are moved into the Delaware PMS. It is rare for data to be questioned. The biggest issue that may be encountered are missing records.

Maryland

For bridges, a supervisor reviews the inspection data based on reports sent by the engineering team lead. These reports are created after the monthly transfer of information to the BMS. Changes to inspections based on this review are rare. Also, an independent internal inspection team will recheck a certain amount of work each year. According to Maryland, approximately 10 percent of the inspections may be verified by this other team.

For roads, office staff review the data received from ARA. It is rare for these data to be questioned or adjusted.

Virginia

For bridges, a bridge safety engineer reviews data at the end of the inspection process. This happens both at the district and state level. Inspection updates are infrequent but any changes are entered directly into the State's Pontis system.

For roads, the IT team responsible for loading the inspection data performs a QA process that includes comparing data summaries generated both inside and outside the PMS. In addition, a third party will review and verify approximately five percent of the records. Inspection data rarely are questioned. However, the team does look for and check large discrepancies in the year-to-year data for any given segment.

Data Interpretation

Numerical measures provide one means of quantifying the condition of a bridge or a pavement section. However, there also is a natural desire to classify asset conditions as "good" or "fair" or "poor" in order to obtain a qualitative assessment of the health of a network.

For bridges, the states participating in this study indicated that they rarely use health index to represent asset condition. Instead they rely on the traditional measures of structurally deficient and functionally obsolete. It is true that functional obsolescence is not considered in the health index calculation. When scheduling maintenance and other activities, states deal with bridges as discrete items. However, when expressing the overall condition of their bridge network, states typically would target "less than five percent of all bridges are structurally deficient", which was the goal expressed by Delaware.

Delaware

For pavement, Delaware defines characteristics for low, medium, and high severity and extent for different pavement types. Table 4.10 shows the definitions used to judge distress severity for flexible pavement. Table 4.11 shows the definitions for distress extent for flexible pavement. Severity and extent for pavement sections feed into the distress conversion tables, shown in Figure 4.4, which are used to compute OPC. OPC is a value between 0 (worse condition) and 100 (best condition). Delaware categorizes OPC as follows: <= 50 is poor, > 50 and <= 60 is fair, and > 60 is good. Because Delaware previously collected IRI only for HPMS sections, the state has not defined any qualitative categories for this measure.

Table 4.10 Delaware Pavement Distress Definitions for Severity

Distress	Low	Medium	High
Fatigue Cracking	Fine parallel hairline cracks	Alligator crack pattern clearly developed	Alligator crack pattern clearly developed with spalling and/or distortion
Transverse Cracking	Crack < 1/4 inch wide	Crack Width > 1/4 and < 3/4 inch and/or spalls less than 3 inches in width or sealed crack with sealant in good condition	Crack Width > 3/4 inch and/or spalls greater than 3 inches in width or significant loss of material
Block Cracking	Crack < 1/4 inch wide	Crack Width > 1/4 and < 3/4 inch and/or spalls less than 3 inches in width or sealed crack with sealant in good condition	Crack Width > 3/4 inch and/or spalls greater than 3 inches in width or significant loss of material
Patch Deterioration	Patches showing little or no defects with a smooth ride	Patches showing medium severity defects (e.g., cracking) and/or notable roughness	Patches showing high-severity defects and/or distinct roughness
Surface Defects	Aggregate has begun to wear away	Aggregate has worn away and surface is becoming rough and/or minor rutting occurring from horse and buggy traffic (less than 1 inch average depth)	Aggregate has worn away and surface is very rough and/or major rutting occurring from horse and buggy traffic (greater than 1 inch average depth)

Source: Delaware Department of Transportation.

Table 4.11 Delaware Pavement Distress Definitions for Extent

Distress	Low	Medium	High
Fatigue Cracking	1-9% (wheel path)	10-25%	> 25%
Transverse Cracking	> 50 foot spacing	25 foot < spacing <50 foot	< 25 foot spacing
Block Cracking	1-9%	10-25%	> 25%
Patch Deterioration	1-9%	10-25%	> 25%
Surface Defects	1-9%	10-25%	> 25%

Source: Delaware Department of Transportation.

Maryland

For pavement, Maryland collects absolute measures and then computes an index measure based on the definitions shown in Table 4.12.

Table 4.12 Maryland Pavement Distress Condition Indexes and Descriptions

Distress	Measurement	Condition Description	Condition Index
IRI (inch/mile)	> 0 and < 60	Very Good	1
	>= 60 and < 95	Good	2
	>= 95 and <= 170	Fair	3
	> 170 and <= 220	Mediocre	4
	> 220 and <= 640	Poor	5
Cracking Index	>= 90 and <= 100	Very Good	1
	>= 80 and < 90	Good	2
	>= 65 and < 80	Fair	3
	>= 50 and < 65	Mediocre	4
	> 0 and < 50	Poor	5
Friction Number	< 35	Poor	1
	>= 35 and < 40	Mediocre	2
	>= 40	Acceptable	3
Percent Rutting > one-half-inch	< 10%	Very Good	1
	>= 10% and < 20%	Fair	2
	>= 20%	Poor	3

Source: Maryland State Highway Administration.

Virginia

For pavement, Virginia provides guidelines, presented in Table 4.13, on how to measure and determine the severity of different types of cracking.

Table 4.13 Virginia Pavement Crack Severity Definitions

Distress	Severity Level	Severity Description	How to Measure
Transverse Cracking	Severity 1	A crack with the sealant in good condition such that the crack width cannot be determined or a closed, unsealed crack.	Record length of transverse cracks at each severity level. Evaluate each crack by highest severity level present on a significant portion of the crack as it is traversed.
	Severity 2	An open, unsealed crack or any crack (sealed or unsealed) with adjacent (within one foot) random cracking.	
Longitudinal Cracking	Severity 1	A crack with the sealant in good condition such that the crack width cannot be estimated or a closed, unsealed crack.	The minimum length of longitudinal cracking counted is one foot. Only longitudinal cracking outside the wheel paths is counted as longitudinal and each occurrence is counted separately. Longitudinal cracking in the wheel paths is counted as Severity 1 alligator cracking. Measure the length of each crack by severity level as it is traversed. Rate
	Severity 2	An open, unsealed crack or any crack (sealed or unsealed) with adjacent random cracking.	

Distress	Severity Level	Severity Description	How to Measure
			each crack at the highest severity level present on a significant portion of the crack. Report the total length of cracking by severity level for the section.
Alligator Cracking	Severity 1	A single sealed or unsealed longitudinal crack in the wheel path or an area of cracks with no or few interconnecting cracks with no spalling.	Considering only the left and right wheel paths, measure the affected area (square feet) at each severity level. Consider only one severity level for a given area. If different severity levels in an area cannot be distinguished, rate the area at the highest severity level. The width of alligator cracking shall be the actual width while a minimum width for all severity levels shall be one foot. Report the square feet of alligator cracking by severity level for the section.
	Severity 2	An area of interconnecting cracks forming the characteristic alligator pattern; may have slight spalling.	
	Severity 3	An area of moderately or severely spalled cracks forming the characteristic alligator pattern.	

Source: Virginia Department of Transportation.

Virginia also categorizes both IRI and CCI, as shown in Table 4.14. Virginia refers to CCI as "pavement condition" while referring to IRI as "ride quality".

Table 4.14 Virginia CCI and IRI Condition Categories

	Measurement	Pavement Condition / Ride Quality
CCI	>= 90	Excellent
	>= 70 and < 90	Good
	>= 60 and < 70	Fair
	>= 50 and < 60	Poor
	< 50	Very Poor
IRI	< 60	Excellent
	>= 60 and < 100	Good
	>= 100 and < 140	Fair
	>= 140 and < 200	Poor
	>= 200	Very Poor

Source: Virginia Department of Transportation.

4.3 Measures Available in ICAT

Following the analysis of the bridge and pavement data, CS selected certain measures to be displayed in the ICAT web application (WebCAT). Consistent with the design presented in Section 5, CS selected approximately six measures for bridges and six for pavement. These measures were incorporated as standard ArcGIS-compatible layers that are accessed using functionality already available in the WebCAT.

At the present time, the modified WebCAT system may be accessed at: http://ags.camsys.com/hpm/index.html.

The WebCAT created in conjunction with this project is a modified version of the WebCAT originally developed for the I-95 Corridor Coalition. The intent is to transition production hosting for the I-95 WebCAT at some point in the future to the University of Maryland. At the time of this transition, FHWA and the I-95 Corridor Coalition must determine the future of the modified WebCAT created for this project.

Within the WebCAT interface, bridge measures for this project are contained within the category "Bridges (Mid-Atlantic)" while the pavement measures for this project are under "Pavement (Mid-Atlantic)". The following sections describe each measure. Each description is followed by a table that shows the asset count based on the current data. Pavement tables also include total miles (rounded), which are computed by summing the difference between the beginning and ending milepoint for each segment. Note that the counts are not consistent because of minor variations in the data (e.g., based on its specific data, a bridge may or may not have a valid sufficiency rating and/or health index).

Also note that CS does not characterize any data as "good," "fair," "poor," etc. These characterizations, where they are used, either come from a state participating in this study or an external source, such as NBIAS. In some cases, data are divided into categories arbitrarily for purposes of comparing different measures for the same assets. These ranges are not intended to represent quality ratings.

Bridges (Mid-Atlantic)

- **SD/FO –** Shows whether a bridge is structurally deficient (SD), functionally obsolete (FO), or not deficient (ND). All bridges on I-95 are included. Bridges that are SD are colored red. Bridges that are FO are colored yellow. Bridges that are not deficient are colored green. This layer provides a means to visualize the current SD/FO status of each bridge. The SD/FO status, in combination with the sufficiency rating, determines whether a bridge is eligible for Federal funding.

State	SD	FO	ND	Total
Delaware	1	9	52	62
Maryland	1	0	82	83
Virginia	24	33	247	304
Total	26	42	381	449

- **Sufficiency Rating (NBIAS) –** Represents the sufficiency rating for the bridge using same the good/fair/poor classifications included in the latest version of the FHWA National Bridge Investment Analysis System (NBIAS). All bridges on I-95 where the value of the sufficiency rating is > 0 are included. Bridges where the sufficiency rating is <= 50 are colored red (poor). Bridges where the sufficiency rating is > 50 and <= 80 are colored yellow (fair). Bridges where the sufficiency rating is > 80 are colored green (good). This layer provides one means of classifying bridges using the same standard as NBIAS.

State	Good	Fair	Poor	Total
Delaware	34	26	0	60
Maryland	10	33	1	44
Virginia	190	102	6	298
Total	234	161	7	402

- **Sufficiency Rating –** Represents the sufficiency rating for the bridge using a five-level classification system based roughly on the available measurements. All bridges on I-95 where the value of the sufficiency rating is > 0 are included. Bridges where the sufficiency rating is <= 60 are colored red. Bridges where the sufficiency rating is > 60 and <= 80 are colored orange. Bridges where the sufficiency rating is > 80 and <= 90 are colored yellow. Bridges where the sufficiency rating is > 90 and <= 95 are colored blue. Bridges where the sufficiency rating is > 95 are colored green. This layer provides an alternate means of classifying bridges.

State	Green	Blue	Yellow	Orange	Red	Total
Delaware	8	14	12	24	2	60
Maryland	1	0	9	32	2	44
Virginia	62	36	92	86	22	298
Total	71	50	113	142	26	402

- **Health Index – Overall –** Represents the overall health index for the bridge using the same five-level classification system used for sufficiency rating. All bridges on I-95 where the value of the sufficiency rating is > 0 are included. Note: this bridge set was chosen deliberately to ensure that the same bridges are available in both this layer and the sufficiency rating layer. Bridges where the health index is <= 60 are colored red. Bridges where the health index is > 60 and <= 80 are colored orange. Bridges where the health index is > 80 and <= 90 are colored yellow. Bridges where the health index is > 90 and <= 95 are colored blue. Bridges where the health index is > 95 are colored green. This layer provides an alternate means of classifying bridges and a way to visually compare the classification of bridges by health index with the classification by sufficiency rating.

State	Green	Blue	Yellow	Orange	Red	Total
Delaware	26	21	10	4	0	61
Maryland	9	6	2	5	1	23
Virginia	150	38	55	55	6	304
Total	185	65	67	64	7	388

- **SR HIX Diff –** Represents the absolute value of the difference between the Sufficiency Rating (SR) and the Health Index – Overall (HIX), both of which are values between 0 and 100. All bridges on I-95 with both a valid sufficiency rating and health index are included. Bridges where the difference is <= 20 are colored green. Bridges where the difference is > 20 and <= 50 are colored yellow. Bridges where the difference is > 50 are colored red. This layer is designed to highlight bridges where there is a substantial difference between these two composite measures.

State	Small Diff	Medium Diff	Large Diff	Total
Delaware	46	14	0	60
Maryland	13	3	0	16
Virginia	239	58	1	298
Total	298	75	1	374

- **Deck Area –** Represents the bridge deck area (in square meters) using a five-level classification system. All bridges on I-95 where the value of the deck area is > 0 are included. Bridges with deck area <= 1,000 square meters are represented by a small circle. Bridges with deck area > 50,000 square meters are represented by a large circle. Between these extremes are three ranges where the size of the circle increases with the size of the deck. These three ranges are > 1,000 and <= 5,000 square meters, > 5,000 and <= 15,000 square meters, and > 15,000 and <= 50,000 square meters. This layer provides a means of visually separating bridges by size.

State	Small	Sm/Med	Medium	Med/Lg	Large	Total
Delaware	33	22	2	1	3	61
Maryland	20	36	1	1	1	59
Virginia	90	80	11	3	20	204
Total	143	138	14	5	24	324

- **Bridges (I-95) –** Represents bridges on I-95. Each bridge is represented by a single point. There is no color coding. This layer provides a way to visually locate all bridges on I-95.

State	Total
Delaware	62
Maryland	83
Virginia	304
Total	449

- **Bridges (All) –** Represents all bridges provided by Delaware, Maryland, and Virginia. Each bridge is represented by a single point. There is no color coding. This layer provides a way to visually locate all bridges in the states participating in this study.

Pavement (Mid-Atlantic)

- **CCI G/F/P (Virginia) –** Represents critical condition index using Virginia's criteria for good, fair, and poor. All road segments on I-95 where CCI <> -1 are included. Note that CCI is available only for Virginia. Segments where CCI is < 60 are colored red (poor). Segments where CCI is >= 60 and < 70 are colored yellow (fair). Segments where CCI is >= 70 are colored green (good). This layer provides a way to visualize pavement condition using Virginia criteria.

State	Good	Fair	Poor	Total
Delaware	0 (0 mi)	0 (0 mi)	0 (0 mi)	0 (0 mi)
Maryland	0 (0 mi)	0 (0 mi)	0 (0 mi)	0 (0 mi)
Virginia	117 (228 mi)	27 (50 mi)	40 (72 mi)	184 (350 mi)
Total	117 (228 mi)	27 (50 mi)	40 (72 mi)	184 (350 mi)

- **OPC G/F/P (Delaware) –** Represents overall pavement condition using Delaware's criteria for good, fair, and poor. All road segments on I-95 are included. Note that OPC is available only for Delaware, which provided this value, and Virginia, where this value was computed by CS. Segments where OPC is <= 50 are colored red (poor). Segments where OPC is > 50 and <= 60 are colored yellow (fair). Segments where OPC is > 60 are colored green (good). This layer provides a way to visualize pavement condition using Delaware criteria and to visually compare pavement condition in Virginia using both Virginia and Delaware criteria.

State	Good	Fair	Poor	Total
Delaware	224 (58 mi)	36 (10 mi)	10 (2 mi)	270 (70 mi)
Maryland	0 (0 mi)	0 (0 mi)	0 (0 mi)	0 (0 mi)
Virginia	171 (319 mi)	8 (13 mi)	5 (7 mi)	184 (339 mi)
Total	395 (377 mi)	44 (23 mi)	15 (9 mi)	454 (409 mi)

- **OPC versus CCI –** Represents the absolute value of the difference between CCI, which was supplied by Virginia, and OPC, which was calculated for Virginia using Virginia data and the Delaware algorithm. Both CCI and OPC have values between 0 and 100. All road segments for I-95 are included but this measurement is available only for Virginia. Segments where the difference is <= 13 are colored green. Segments where the difference is > 13 and <= 34 are colored yellow. Segments where the difference is > 34 are colored red. This layer is designed to highlight pavement segments where there is a substantial difference between these two composite measures.

State	Small Diff	Medium Diff	Large Diff	Total
Delaware	0 (0 mi)	0 (0 mi)	0 (0 mi)	0 (0 mi)
Maryland	0 (0 mi)	0 (0 mi)	0 (0 mi)	0 (0 mi)
Virginia	127 (247 mi)	52 (94 mi)	7 (12 mi)	186 (353 mi)
Total	127 (247 mi)	52 (94 mi)	7 (12 mi)	186 (353 mi)

- **IRI G/F/P (Maryland) –** Represents IRI using Maryland's criteria for good, fair, and poor. All road segments on I-95 are included. Segments where IRI is <= 95 are colored green (good). Segments where IRI is > 95 and <= 170 are colored yellow (fair). Segments where IRI is > 170 are colored red (poor). This layer provides a way to visualize pavement condition based on IRI using Maryland criteria.

State	Good	Fair	Poor	Total
Delaware	58 (21 mi)	30 (5 mi)	32 (5 mi)	120 (31 mi)
Maryland	1627 (163 mi)	328 (33 mi)	135 (14 mi)	2090 (210 mi)
Virginia	118 (231 mi)	66 (108 mi)	0 (0 mi)	184 (339 mi)
Total	1803 (415 mi)	424 (146 mi)	167 (19 mi)	2394 (580 mi)

- **IRI G/F/P (Virginia) –** Represents IRI using Virginia's criteria for good, fair, and poor. All road segments on I-95 are included. Segments where IRI is < 100 are colored green (good). Segments where IRI is >= 100 and < 140 are colored yellow (fair). Segments where IRI is >= 140 are colored red (poor). This layer provides a way to visualize pavement condition based on IRI using Virginia criteria and to visually compare pavement condition based on IRI using both Maryland and Virginia criteria.

State	Good	Fair	Poor	Total
Delaware	59 (21 mi)	22 (4 mi)	39 (5 mi)	120 (30 mi)
Maryland	1662 (166 mi)	187 (19 mi)	241 (24 mi)	2090 (209 mi)
Virginia	126 (247 mi)	54 (87 mi)	4 (5 mi)	184 (339 mi)
Total	1847 (434 mi)	263 (110 mi)	284 (34 mi)	2394 (578 mi)

- **IRI Condition (Maryland) –** Represents the IRI Condition Index provided by Maryland. All road segments on I-95 in Maryland are included where the index value is 1, 2, 3, 4, or 5. Segments where the index is 1 are colored green (very good). Segments where the index is 2 are colored blue (good). Segments where the index is 3 are colored yellow (fair). Segments where the index is 4 are colored orange (mediocre). Segments where the index is 5 are colored red (poor). This layer provides a way to visualize another distress condition using Maryland data and ratings.

State	Very Good	Good	Fair	Mediocre	Poor	Total
Delaware	0 (0 mi)	0 (0 mi)	0 (0 mi)	0 (0 mi)	0 (0 mi)	0 (0 mi)
Maryland	804 (80 mi)	820 (82 mi)	338 (34 mi)	86 (9 mi)	50 (5 mi)	2098 (210 mi)
Virginia	0 (0 mi)	0 (0 mi)	0 (0 mi)	0 (0 mi)	0 (0 mi)	0 (0 mi)
Total	804 (80 mi)	820 (82 mi)	338 (34 mi)	86 (9 mi)	50 (5 mi)	2098 (210 mi)

- **Crack Condition (Maryland) –** Represents the Crack Condition Index provided by Maryland. All road segments on I-95 in Maryland are included where the index value is 1, 2, 3, 4, or 5. Segments where the index is 1 are colored green (very good). Segments where the index is 2 are colored blue (good). Segments where the index is 3 are colored yellow (fair). Segments where the index is 4 are colored orange (mediocre). Segments where the index is 5 are colored red (poor). This layer provides a way to visualize another distress condition using Maryland data and ratings.

State	Very Good	Good	Fair	Mediocre	Poor	Total
Delaware	0 (0 mi)	0 (0 mi)	0 (0 mi)	0 (0 mi)	0 (0 mi)	0 (0 mi)
Maryland	1642 (164 mi)	153 (15 mi)	73 (7 mi)	14 (1 mi)	0 (0 mi)	1882 (187 mi)
Virginia	0 (0 mi)	0 (0 mi)	0 (0 mi)	0 (0 mi)	0 (0 mi)	0 (0 mi)
Total	1642 (164 mi)	153 (15 mi)	73 (7 mi)	14 (1 mi)	0 (0 mi)	1882 (187 mi)

- **Rut Condition (Maryland) –** Represents the Rut Condition Index provided by Maryland. All road segments on I-95 in Maryland are included where the index value is 1, 2, or 3. Segments where the index is 1 are colored green (very good). Segments where the index is 2 are colored yellow (fair). Segments where the index is 3 are colored red (poor). This layer provides a way to visualize another distress condition using Maryland data and ratings.

State	Very Good	Fair	Poor	Total
Delaware	0 (0 mi)	0 (0 mi)	0 (0 mi)	0 (0 mi)
Maryland	1754 (175 mi)	85 (9 mi)	258 (26 mi)	2097 (210 mi)
Virginia	0 (0 mi)	0 (0 mi)	0 (0 mi)	0 (0 mi)
Total	1754 (175 mi)	85 (9 mi)	258 (26 mi)	2097 (210 mi)

- **Friction Condition (Maryland) –** Represents the Friction Condition Index provided by Maryland. All road segments on I-95 in Maryland are included where the index value is 1, 2, or 3. Segments where the index is 1 are colored red (poor). Segments where the index is 2 are colored yellow (mediocre). Segments where the index is 3 are colored green (acceptable). This layer provides a way to visualize another distress condition using Maryland data and ratings.

State	Poor	Mediocre	Acceptable	Total
Delaware	0 (0 mi)	0 (0 mi)	0 (0 mi)	0 (0 mi)
Maryland	13 (1 mi)	49 (5 mi)	310 (31 mi)	372 (37 mi)
Virginia	0 (0 mi)	0 (0 mi)	0 (0 mi)	0 (0 mi)
Total	13 (1 mi)	49 (5 mi)	310 (31 mi)	372 (37 mi)

- **IRI –** Represents IRI using a four-level classification system. All road segments on I-95 are included. The classification system uses thicker lines for higher values of IRI. The four IRI ranges are <= 75 (thinnest line), > 75 and <= 150, > 150 and <= 225, and > 225 (thickest line). This layer provides a way to visualize IRI.

State	Best	Med/Best	Med/Worst	Worst	Total
Delaware	33 (13 mi)	52 (12 mi)	28 (4 mi)	7 (1 mi)	120 (30 mi)
Maryland	1322 (132 mi)	561 (56 mi)	163 (16 mi)	44 (4 mi)	2090 (208 mi)
Virginia	53 (116 mi)	129 (220 mi)	2 (3 mi)	0 (0 mi)	184 (339 mi)
Total	1408 (261 mi)	742 (288 mi)	193 (23 mi)	51 (5 mi)	2394 (577 mi)

4.4 Conclusions and Recommendations

The goal of this study was to use pavement and bridge data from a multi-state interstate corridor to analyze performance measures and evaluate how performance data can be used for corridor management. The project team was charged with acquiring data from three states, establishing candidate measures that summarize performance of pavement sections and bridges, and performing any necessary reductions/transformations of the data. In addition to this technical memorandum, the project deliverables include a revised version of ICAT showing pavement and bridge measures for use by FHWA and I-95 Corridor Coalition members.

Conclusions Regarding Current Results

Historically, sufficiency rating for bridge and IRI for pavement have been the measures that are available, either directly or via calculation by FHWA, to judge the condition of the nation's transportation assets. Based on our review of the pavement and bridge data provided by Delaware, Maryland, and Virginia, CS draws the following conclusions regarding these measures.

- For pavement, IRI does not provide adequate information to judge overall condition. Composite measures that combine a range of distress types into a single index provide a more accurate condition indicator, regardless of the algorithm used to compute the measure. This conclusion is supported by:

- The extent of the engineering analysis used by Virginia to develop their Critical Condition Index;
- The relatively good correlation between CCI, which was provided by Virginia, and OPC, which was calculated using Virginia data and the Delaware algorithm; and
- The relatively poor correlation between IRI and CCI (in Virginia) and between IRI and OPC (in Delaware).

- While Virginia and Delaware (and, presumably, many other states) have defined composite condition measures for pavement that are better than any individual distress rating, it is not clear if these composite measures represent more than the superficial condition of the pavement. Composite measures like CCI and OPC may not correlate well with the structural adequacy of the pavement. CS makes this assumption because the composite measures observed to date consist of weighted combinations of regular distresses (e.g., cracking, rutting, etc.). They do not include more sophisticated readings such as falling weight deflectometer results nor do they take into account the overlay history of the pavement.
- Regardless of its value as an overall indicator of condition, IRI will continue to be a valuable measure of ride quality. At a sufficiently high level, any consistent measure can provide useful information about an asset network because analysts can make judgments about relative condition between states, counties, roads, etc., by comparing "apples to apples". There is an open question of whether IRI is captured consistently across states. However, this is a technical issue that can be overcome by ensuring consistent calibration of data collection instrumentation.
- While states have different interpretations of what constitutes a good/fair/poor value for IRI, these differences, at least within the limited survey for this project, appear not to be significant. This is supported by a visual comparison within the WebCAT of the IRI good/fair/poor ratings provided by Virginia and Maryland. Although the Maryland standard has a significantly wider range for fair (almost twice as wide as Virginia), the differences between these two visualizations are not dramatic.
- For bridges, it is difficult to directly compare sufficiency rating and health index. CS believes that the health index calculation, which is based on detailed element condition information weighted by the relative importance (i.e., failure cost) of each element, provides a superior measure of structural condition. However, health index does not include any measure of functional adequacy or asset essentiality. This is one reason that bridge engineers have not adopted health index more broadly and continue to rely on the traditional SD/FO ratings.
- The differences in the purpose of sufficiency rating and health index explain the lower correlations between these two values. At this time, however, there

is no justification for choosing one over the other in all circumstances. Depending on the specific area of inquiry, either sufficiency rating or health index may provide a more accurate answer (e.g., studies looking specifically at structural health would benefit more from using the health index).

- While the correlations between sufficiency rating and health index did not meet the threshold adopted for this study, they generally were not as low as the correlations between IRI and CCI or OPC. This particularly was true when comparing individual NBI ratings (e.g., deck, superstructure, substructure) with equivalent health index subcomponents. This may reflect a greater degree of uniformity in bridge inspection, which likely is driven by the more comprehensive NBI standard and the near-universal adoption of the Pontis BMS. This also reinforces the previous conclusion that sufficiency rating and health index both are adequate, albeit slightly different, measures of condition.
- States generally do not categorize sufficiency rating as good/fair/poor preferring instead to focus on whether or not a bridge qualifies for Federal funding. In the absence of a more compelling standard, it makes sense to coordinate with NBIAS and adopt the standards used by this program, if this type of categorization is needed. This will help ensure consistency when comparing NBI values with standard NBIAS reports.

Recommendations for Alternative Measures

Transportation asset management is a set of guiding principles and best practices for making informed resource allocation decisions and improving accountability for these decisions. Performance measures are a fundamental building block for any asset management effort. Defining these performance measures helps organizations support asset management in three basic ways:

1. Performance measures can be used to quantify policy goals and objectives in a practical way;
2. Performance measures help agencies evaluate resource allocation options and determine how to prioritize different investments and/or compare the impact of different funding levels; and
3. Performance measures provide a quantitative means to measure progress, determine program effectiveness, and chart trends over time.

When considering existing performance measures for bridges and pavement sections, the analysis performed during this project suggests that adequate measures exist for bridges but not for pavement. The following are the findings and recommendations for this analysis.

- **Finding –** CS believes that sufficiency rating and health index both are useful measures for bridges. Between them, they address the key factors of physical condition, functional adequacy, and asset importance. The current NBI standard provides the information necessary for FHWA to compute sufficiency rating in a uniform manner at a national level. However, health index, which provides a better measure of physical condition than does sufficiency rating, is not available outside of an individual state running Pontis.

- **Recommendation –** In order to provide FHWA with access to health index values for the national bridge network, CS recommends that FHWA consider modifying the NBI submission from states to include some element data. The element data could be added to the current NBI file or submitted in a second NBI-Element file. Many states already have element data available and, once a new NBI structure has been defined, bridge management systems could be programmed to include this information with little or no additional effort for the states. FHWA would require a process to read/store the element data and a program to compute health index using this information. This Pontis-independent program would be similar to the one currently used to compute sufficiency rating and, like with sufficiency rating, FHWA would provide the calculated health index back to the states. FHWA also would adopt standards for element weights, which would ensure the validity of state-to-state comparisons of health index. Elements usually are weighted by failure cost, although the health index calculation also can use the cost of the most expensive action. However, these costs are not required. A health index can be produced using any weight factor that establishes the relative importance of the elements. This recommendation would be a natural follow-up to the current effort by the AASHTO Subcommittee on Bridges and Structures, Technical Committee T-18 on Bridge Management, Evaluation, and Rehabilitation to redefine bridge elements.
- **Finding –** CS believes that composite values provide a better picture of pavement condition than individual measures like IRI. The HPMS Reassessment 2010+ will add significant new information on pavement distress and history. However, at this time, there is no reason to believe that any of these additional items, if used in isolation, will provide a significantly better measure of condition than IRI.
- **Recommendation –** CS recommends that FHWA use the new HPMS 2010+ information as the foundation for developing one or more Federally approved composite values (e.g., "health indices" for pavement) that can serve as measures of structural adequacy, load-bearing capacity, remaining service life, etc., for pavement sections. As part of this process, CS also recommends that FHWA undertake a more thorough review of composite pavement condition algorithms used by states with an eye toward either adopting one or, more likely, developing a custom algorithm that leverages the existing work but is based on HPMS 2010+ data elements.
- **Finding –** The focus on ride quality may have led some states to emphasize cosmetic treatments that improve the road surface but which do not address underlying structural problems. It is true that surface condition (and ride quality) are key concerns of the traveling public. However, this type of

policy may be concealing significant roadway problems that must be addressed in the future.

- **Recommendation –** CS recommends that FHWA, either directly or in partnership with one or more states, test sample road sections and solicit expert engineering advice to determine whether any relationship exists between health indexes computed using current distress values and the actual road condition. The goal will be to assess values such as carrying capacity and remaining service life (i.e., time to next major rehabilitation) and incorporate this information into pavement composite measures described previously. This will turn a composite measure of condition into a true measure of structural adequacy.

- **Finding –** Sufficiency rating includes more than just bridge condition. It also incorporates serviceability and functional obsolescence as well as essentiality for public use. Equivalent measures do not always exist for roads. The Highway Economic Requirements System (HERS) does forecast roadway improvements to address functional inadequacies, but these results are more complex than SD/FO ratings for bridges. Also, HERS only recommends improvements that are justifiable from a benefit/cost perspective, which is not how sufficiency rating works.

- **Recommendation –** In order to address this issue, CS recommends that FHWA define models of functional obsolescence and public importance for roads. These models could borrow from concepts already present in HERS but would be simpler to implement and interpret. CS believes that these measures may not carry the same weight for roads that they do for bridges because the road network is more extensive, has many alternate paths, and is less susceptible to catastrophic failure. However, even if these models are applied only to the interstate network, the information they provide could be used to understand the criticality of the structural adequacy measures discussed previously.

  At the same time, FHWA should consider whether benefit/cost criteria similar to those used in HERS should be incorporated into the functional obsolescence component of the sufficiency rating calculation for bridges. This change could make the sufficiency rating a more effective measure.

5.0 Design Report: Condition Indicator Display Capability in ICAT

This section contains the design report for incorporating the display of bridge and pavement condition information into the ICAT web application (WebCAT). The goal of this task was to provide users with the capability to use the WebCAT map interface to select a section of Interstate 95 in Virginia, Maryland, and/or Delaware and to overlay information representing bridge and pavement condition measures.

5.1 WebCAT Environment

Geodatabase

The ICAT geodatabase was built using ESRI's ArcGIS Server 9.3. ArcGIS Server includes SDE (Spatial Database Engine), which is used to spatially enable a relational database management system (RDBMS). For ICAT, the RDBMS is Microsoft SQL Server 2005. SQL Server and SDE together form a geodatabase, which holds all information displayed within WebCAT.

Web Application

The WebCAT web application is an Adobe Flex program that uses the ESRI Flex Map application programming interface (API) to communicate with ArcGIS Server. ESRI developed a sample web application called FlexViewer, which is written using Adobe Flex and the ActionScript programming language. The WebCAT web application is a customized version of the FlexViewer web application.

5.2 WebCAT Design

The application framework used for the WebCAT provides a standard architecture for incorporating new geographically tagged information. No custom elements or programming were required for this effort. The following steps were used to add map layers containing bridge and pavement condition data:

- As described in Section 3.4, common data structures were defined for the bridge and pavement data. These structures were created as tables in the SDE geodatabase. The bridge table contains one record for each bridge and the pavement table contains one record for each pavement section. Each record in these tables includes:

  - Sufficient information to position the bridge or pavement section on the ICAT network;
  - A set of condition measures associated with the bridge or pavement section; and
  - Any other relevant information associated with the bridge or pavement section. For example, the bridge table contains a subset of the NBI items for each bridge.

  A database structure for bridges is shown in Table 5.1 and a structure for pavement is shown in Table 5.2. These database structures also include columns that contain calculated performance measures.

- ArcMap, part of ArcGIS desktop, was used to create a set of map services. A map service defines:
  - The data to be included (e.g., pavement sections);
  - A condition measure to be categorized (e.g., IRI);
  - A method for categorizing the condition measure (e.g., by value range); and
  - Display characteristics for the condition measure categories (e.g., lines of different widths or colors).

  The specifics of these map services (i.e., the condition measures and the ways in which they are categorized) are documented in Section 4.3.

- ArcCatalog, another part of ArcGIS desktop, was used to publish the map services to ArcGIS Server.
- The WebCAT configuration files were updated to incorporate the map services as additional data layers into the WebCAT application.

Table 5.1 Bridge Database Structure

Column Name	Data Type	Description
State	CHAR(2)	State Code
County Code	CHAR(3)	County Code received from state
BRKEY	VARCHAR(16)	Bridge Key
Route ID	VARCHAR(40)	Route ID received from state or calculated from state values
ON_UNDER	NUMBER(1)	Record Type
KIND_HWY	NUMBER(1)	Route Signing Prefix
LEVL_SRVC	NUMBER(1)	Designated Level of Service
ROUTENUM	CHAR(5)	Route Number
DIRSUFFIX	CHAR(1)	Directional Suffix

Column Name	Data Type	Description
ROADWAY_NAME	VARCHAR(25)	Roadway Name
KMPOST	NUMBER(4,3)	Kilometer Point
FACILITY	VARCHAR(18)	Facility Carried
LOCATION	VARCHAR(25)	Location
FEATINT	VARCHAR(25)	Features Intersected
LATITUDE	NUMBER(8)	Latitude
LONGITUDE	NUMBER(9)	Longitude
CRIT_FEAT	CHAR(1)	Critical Feature
TOLLFAC	NUMBER(1)	Toll
FUNCCLASS	NUMBER(2)	Functional Class
LANES	NUMBER(4)	Lanes On/Under
ADTTOTAL	NUMBER(6)	Average Daily Traffic
ADTYEAR	NUMBER(4)	Year of Average Daily Traffic
TRAFFICDIR	NUMBER(1)	Direction of Traffic
TRUCKPCT	NUMBER(2)	Average Daily Truck Traffic
ADTFUTURE	NUMBER(6)	Future Average Daily Traffic
ADTFUTUREYEAR	NUMBER(4)	Year of Future Average Daily Traffic
DECK_AREA	NUMBER(10,5)	Deck Area
TEV_WEIGHT	NUMBER(10,1)	Total Element Value Weight (entire bridge)
CEV_WEIGHT	NUMBER(10,1)	Current Element Value Weight (entire bridge)
HIX_WEIGHT	NUMBER(3,1)	Health Index (entire bridge)
TEV_WEIGHT_DECK	NUMBER(10,1)	Total Element Value Weight (deck only)
CEV_WEIGHT_DECK	NUMBER(10,1)	Current Element Value Weight (deck only)
HIX_WEIGHT_DECK	NUMBER(3,1)	Health Index (deck only)
TEV_WEIGHT_SUPER	NUMBER(10,1)	Total Element Value Weight (superstructure only)
CEV_WEIGHT_SUPER	NUMBER(10,1)	Current Element Value Weight (superstructure only)
HIX_WEIGHT_SUPER	NUMBER(3,1)	Health Index (superstructure only)
TEV_WEIGHT_SUB	NUMBER(10,1)	Total Element Value Weight (substructure only)
CEV_WEIGHT_SUB	NUMBER(10,1)	Current Element Value Weight (substructure only)
HIX_WEIGHT_SUB	NUMBER(3,1)	Health Index (substructure only)
DKRATING	CHAR(1)	Deck Rating
SUPRATING	CHAR(1)	Superstructure Rating
SUBRATING	CHAR(1)	Substructure Rating
CULVRATING	CHAR(1)	Culvert Rating
STRRATING	CHAR(1)	Structural Rating
NBI_RATING	CHAR(1)	NBI Rating
SUFF_RATE	NUMBER(3,1)	Sufficiency Rating
SUFF_PREFX	CHAR(1)	Sufficiency Rating Prefix
SR_HIX_DIFF	NUMBER(10,1)	Difference Between SUFF_RATE and HIX_WEIGHT

Table 5.2 Pavement Database Structure

Column Name	Data Type	Description
State	CHAR(2)	State Code
County Code	CHAR(3)	County Code received from state (only for MD and VA)
Route ID	VARCHAR(40)	Route ID received from state or calculated from state values
Road Name	VARCHAR(100)	Road Name received from state (only for DE)
Beg MP	NUMBER(7,3)	Beginning Milepoint
End MP	NUMBER(7,3)	Ending Milepoint
Length	NUMBER(7,3)	Segment Length (only for VA)
IRI_L	NUMBER(3)	IRI Left (only for DE and VA)
IRI_R	NUMBER(3)	IRI Right (only for DE and VA)
IRI_Avg	NUMBER(3)	IRI Average
T_CR1_LF	NUMBER(5)	Transverse Cracking Severity 1 (only for VA)
T_CR2_LF	NUMBER(5)	Transverse Cracking Severity 2 (only for VA)
L_CR1_LF	NUMBER(5)	Longitudinal Cracking Severity 1 (only for VA)
L_CR2_LF	NUMBER(5)	Longitudinal Cracking Severity 2 (only for VA)
L_JT1_LF	NUMBER(5)	Longitudinal Lane Joint Severity 1 (only for VA)
L_JT2_LF	NUMBER(5)	Longitudinal Lane Joint Severity 2 (only for VA)
RT_CR1_LF	NUMBER(5)	Reflective Transverse Cracking Severity 1 (only for VA)
RT_CR2_LF	NUMBER(5)	Reflective Transverse Cracking Severity 2 (only for VA)
RT_CR3_LF	NUMBER(5)	Reflective Transverse Cracking Severity 3 (only for VA)
RL_CR1_LF	NUMBER(5)	Reflective Longitudinal Cracking Severity 1 (only for VA)
RL_CR2_LF	NUMBER(5)	Reflective Longitudinal Cracking Severity 2 (only for VA)
RL_CR3_LF	NUMBER(5)	Reflective Longitudinal Cracking Severity 3 (only for VA)
A_CR1_SF	NUMBER(5)	Alligator Cracking Severity 1 (only for VA)
A_CR2_SF	NUMBER(5)	Alligator Cracking Severity 2 (only for VA)
A_CR3_SF	NUMBER(5)	Alligator Cracking Severity 3 (only for VA)
PA_WP_SF	NUMBER(6)	Patching Area – Wheel Path (only for VA)
PA_NWP_SF	NUMBER(6)	Patching Area – Nonwheel Path (only for VA)
POT_NO	NUMBER(3)	Pothole Count (only for VA)
DELAM_SF	NUMBER(5)	Delamination Area (only for VA)
BLEED1_SF	NUMBER(5)	Bleeding Severity 1 (only for VA)
BLEED2_SF	NUMBER(5)	Bleeding Severity 2 (only for VA)
RUT_S_AVG	NUMBER(5,2)	Average Rut Depth – Straight Edge (only for VA and MD)
RUT_W_AVG	NUMBER(5,2)	Average Rut Depth – Wire Method (only for VA and MD)
LDR	NUMBER(3)	Load Distress Rating (only for VA)
NDR	NUMBER(3)	Nonload Distress Rating (only for VA)
CCI	NUMBER(3)	Critical Condition Index (only for VA)
Latitude Start	NUMBER(15,10)	Latitude at start of segment (only for VA)
Longitude Start	NUMBER(15,10)	Longitude at start of segment (only for VA)

Column Name	Data Type	Description
Latitude End	NUMBER(15,10)	Latitude at end of segment (only for VA)
Longitude End	NUMBER(15,10)	Longitude at end of segment (only for VA)
OPC	NUMBER(6,2)	Overall Pavement Condition (only for DE)
IRI Condition	NUMBER(1)	IRI Condition Index (only for MD)
Rut Count	NUMBER(5,2)	Rut Count (only for MD)
Rut Condition	NUMBER(1)	Rut Condition Index (only for MD)
Friction Number	NUMBER(5,2)	Friction Number (only for MD)
Friction Condition	NUMBER(1)	Friction Condition Index (only for MD)
Cracking Index	NUMBER(5,2)	Cracking Index (only for MD)
Crack Condition	NUMBER(1)	Cracking Condition Index (only for MD)
OPC_VS_CCI	NUMBER(6,2)	Difference Between OPC and CCI

User Interface Changes

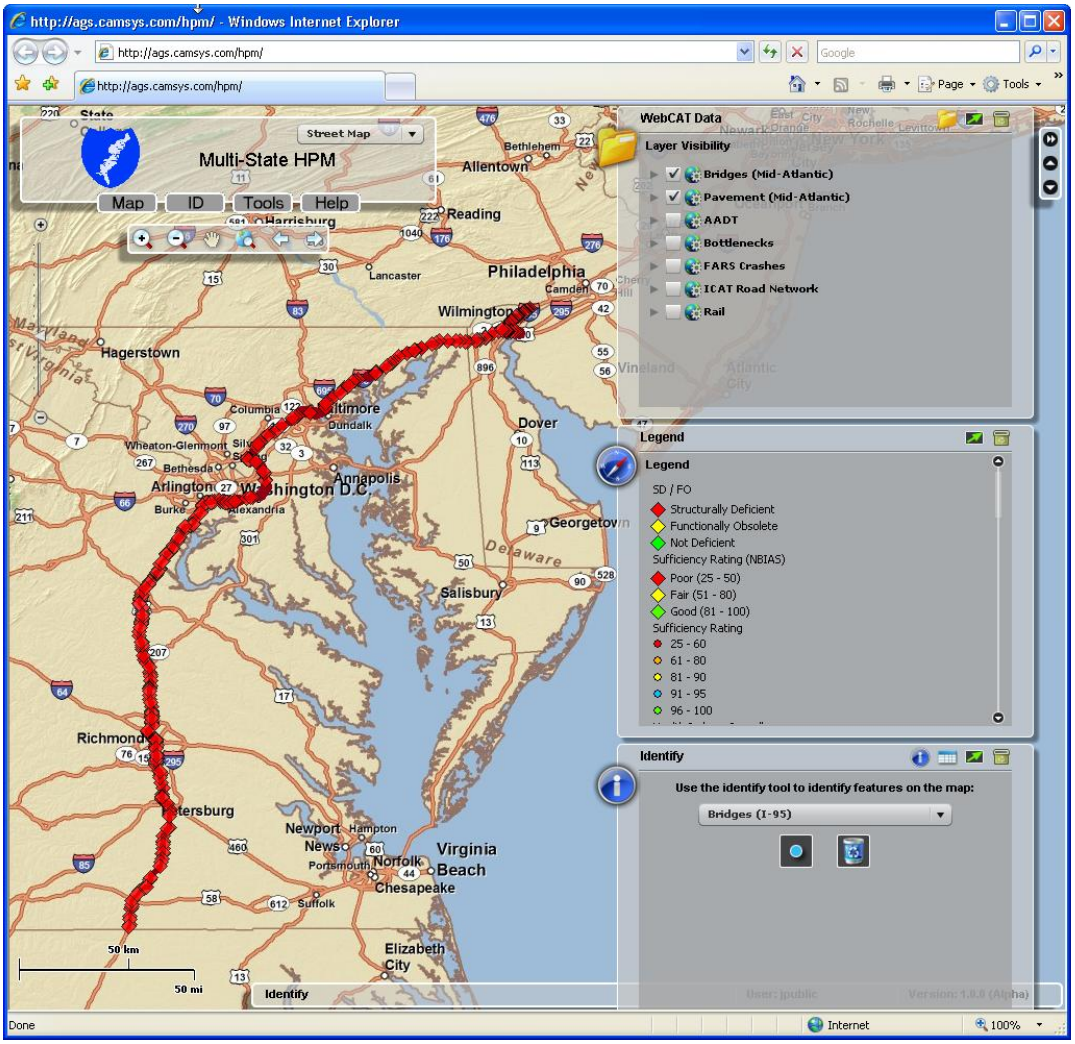
Integration of bridge and pavement condition measures into WebCAT manifests itself in three places (refer to Figure 5.1):

1. Additional data layers are available within the WebCAT data toolbox. This toolbox is displayed by selecting "WebCAT Data" under the Map menu item. These additional data layers correspond to the map services described previously.

   Under the heading "Bridges (Mid-Atlantic)", options represent the ways in which bridges are categorized. For example, one option is "Health Index – Overall," which categorizes bridges based on a set of health index ranges. Each category is represented visually using icons of different colors.

   A heading called "Pavement (Mid-Atlantic)" contains a set of options by which pavement sections are categorized. For example, one option is "IRI," which categorizes pavement sections based on a set of IRI ranges. The line representing each pavement section is shown using a different width based on the IRI category for that section.

Figure 5.1 WebCAT User Interface



2. Each map service also appears as an option in the Identify toolbox. This toolbox is displayed by selecting "Identify" under the ID menu item.

   Using the Identify tool, users can click on a specific bridge or pavement section to see detailed information. The information is pulled from the bridge or pavement tables in the geodatabase. This process displays most of the data available for the selected item, excluding elements used only for internal purposes.

3. The legend was updated to include information on the different condition measure categories. This information helps in interpreting the visual information contained in each map layer. Note that the legend currently is a static image and contains information for all map layers. The user must manually locate the specific portion of the legend that applies to the layer that is displayed.

Issues

Data for specific bridges and pavement sections may be missing. This could manifest itself in one of two ways:

- The entire bridge/section is missing from the data table – in this case, the object would not appear in any of the data layers created for this project; or
- The bridge/section is available but a particular performance measure could not be calculated – in this case, the object would not appear only when certain data layers are selected.

Section 4.3 discusses gaps in the base data and how these affect the performance measures calculated from these data as well as the display of the different layers.

When multiple data layers are selected, they are drawn on the base map in order from bottom to top. Given that there are a limited number of visual options that may be applied to the different performance measure categories, it would be easy to select two data layers where the second completely obscures the first. Section 4.3 identifies the visual display characteristics used for each performance measure. It is up to the user to either display one measure at a time or to select measures that are visually compatible.

For practical reasons, the number of data layers created in the WebCAT was limited to the most interesting condition measures identified during Task 3. In total, eight layers were created using bridge data and 10 layers using pavement data.

5.3 Web-Based Training

FHWA personnel participated in a web-based demonstration and training session on March 9, 2010 for the revised WebCAT. This training covered the process of using WebCAT features as well as the content and display characteristics of each map layer. Following this session, some changes were made to the WebCAT system to address comments received, including the creation of five additional map layers. FHWA personnel then used this system during a two-week test to conduct their own analyses.

The revised WebCAT currently is deployed on a CS server and will remain available for a limited time consistent with policies to be established between the I-95 Corridor Coalition and CS. The University of Maryland is scheduled to take over hosting of the WebCAT at some future time. When this transition occurs, the revised WebCAT developed for this project also may be moved to the University of Maryland.

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