Southern Plains Transportation Center

Towards an Open-Source Web GIS-based Bridge Management System using Advanced Geo-Spatial Data Visualization and Integration Technologies

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16. ABSTRACT

This research project developed and implemented a web GIS-based bridge management system that allows for advanced geospatial visualization and potential data integration on a centralized cloud platform. The specific tasks of this project were: 1) to provide a comprehensive review of current BMS development activities; 2) to identify available bridge-related data sources at the state DOT, which enable the further data integration needed for a variety of analytical purposes; 3) to build a more realistic model to represent the deterioration of bridge components by using a semi-Markov transition process. The semi-Markovian transition probabilities were derived directly by accessing and analyzing the NBI database; and 4) to develop a web GIS-based bridge management system that allows advanced geospatial visualization and potential data integration on a centralized cloud platform. The pertinent bridge maintenance data includes text, images, engineering documents, citizen reports, and remote sensing data.

The research team used Esri™ technology-based ArcGIS Online as the major development tool and the developed BMS is designed as a bi-level platform. The upper level manages the overall bridge network based on two-dimensional (2D) vectors or images, while the lower level handles three-dimensional (3D) spatial information and real-time data streams for monitoring the health of individual bridges. One of the major outcomes of this project is an open source BMS prototype that can meet the need to create custom applications, provide a platform for integrating GIS with other business systems, and enable cross-organizational collaboration. The prototype provides an open-source architecture for the public. Its architecture and codes will be open to end users and thus can be easily customized by any transportation agencies for their bridge management needs.

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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)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		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)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		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)

Acknowledgements

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Towards an Open-Source Web GIS-Based Bridge Management System Using Advanced Geo-Spatial Data Visualization and Integration Technologies

Final Report

November 2018

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Executive Summary

Bridge Management Systems (BMSs) are important means of managing information of bridges used to support decision-making that assures the bridge's long-term health, and to formulate maintenance programs in line with budgetary constraints and funding limitations. An increasing number of infrastructure owners support management of infrastructure with sophisticated, computerized management systems to maximize the benefit to society. However, after over two decades of development, existing BMSs still have many limitations: 1) limited capability of electronically sharing and retrieving data among DOT divisions; 2) nearly no web-based applications; 3) limited capacity of visualizing geospatial data; 4) limited supporting data types (for example, the existing NBI database lacks any imagery data such as remote sensing data, photos, or any public volunteered information); 5) limited capacity for real-time operation; and 6) flat graphics and user-unfriendly interfaces.

To address these issues, this research project developed and implemented a web GIS-based bridge management system that allows for advanced geospatial visualization and potential data integration on a centralized cloud platform. The specific tasks of this project were: 1) to provide a comprehensive review of current BMS development activities; 2) to identify available bridge-related data sources at the state DOT that enable the further data integration needed for a variety of analytical purposes; 3) to build a more realistic model to represent the deterioration of bridge components by using a semi-Markov transition process. The semi-Markovian transition probabilities will be derived directly by accessing and analyzing the NBI database; and 4) to develop a web GIS-based bridge management system that allows advanced geospatial visualization and potential data integration on a centralized cloud platform. The pertinent bridge maintenance data includes text, images, engineering documents, citizen reports and remote sensing data.

The research team used Esri™ technology-based ArcGIS Online to develop a map-centric content management system that stores and integrates data, delivers visualized outputs, and manages user access and security. The developed BMS is designed as a bi-level platform, in which the upper level manages the overall bridge network based on two-dimensional (2D) vectors or images, while the lower level handles three-dimensional

(3D) spatial information and real time data streams for monitoring the health of individual bridges. One major development of this project is to provide an open source BMS prototype that can meet the need to create custom applications, provide a platform for integrating GIS with other business systems, and enable cross-organizational collaboration. The prototype aims to provide an open-source architecture for the public. Its architecture and codes will be open to end users and thus can be easily customized by any transportation agency for their bridge management needs.

The research team completed all of the tasks in a 12-month period with four main phases: 1) conducting a comprehensive review on current BMS development activities and further identifying user and data needs for the proposed BMS; 2) developing a web GIS-based bi-level bridge management platform by utilizing the advancement of modern information technology such as web GIS, Building Information Modeling (BIM), cloud computing, remote data sensing, real-time data feeds, etc.; 3) integrating relevant bridge data into the BMS and developing more realistic models for forecasting bridge life-cycle performance; and 4) developing research reports and guidelines on the proposed BMS, and distributing the prototype to the public as an open-source web GIS-based platform.

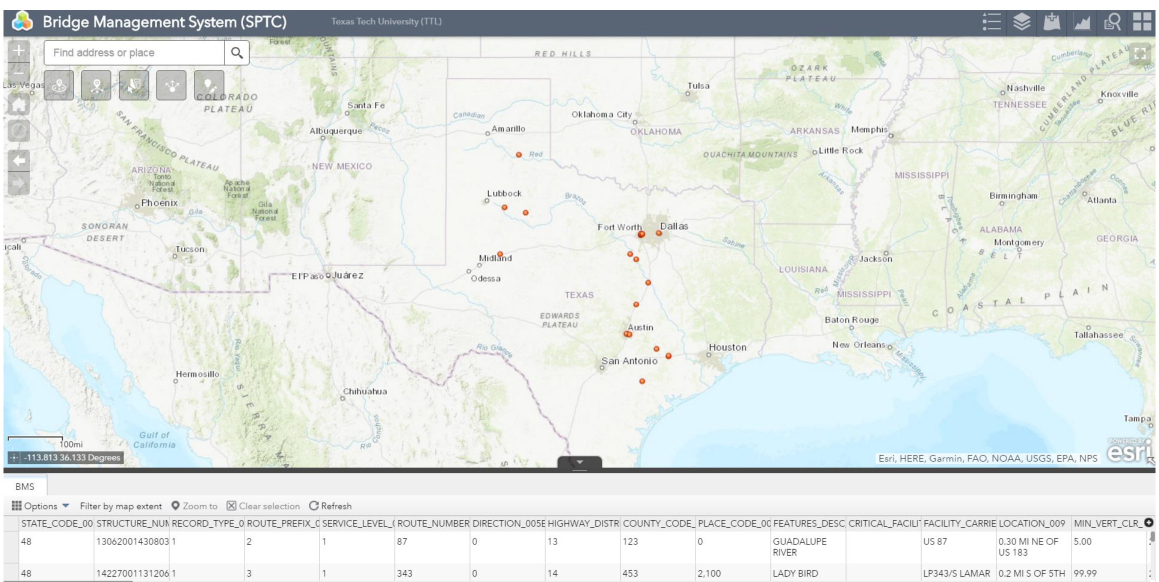

Figure 1 The developed web-GIS based Bridge Management System

1. Introduction

Bridges play a critical role in society operations by ensuring mobility that can sustain social and economic growth. However, recent weather extremes such as record high summer temperatures, flash floods and a large number of freeze-thaw cycles, coupled with poor soils in the states of U.S. Region 6, create increasing challenges to bridges' service life and public safety. Increased truck traffic and limited financial resources available to transportation agencies for construction, maintenance, and preservation of bridges exacerbate these weather-related durability challenges. A renewed awareness of the safety of existing bridges is shared by transportation agencies at all levels of government, including federal, state and municipal.

According to the report from the Federal Highway Administration (FHWA), in the United States, 58,495 bridges out of the 629,539 bridges are currently rated as structurally deficient. This equates to 9.6 percent of the bridge stock in the nation [1]. The American Society of Civil Engineers (ASCE) estimated that the cost of bringing America's infrastructure to a state of good repair by 2020 at $3.6 trillion, of which only about 55 percent has been committed [2]. As a means of managing information of bridges to support decision-making that assures their long-term health and to formulate maintenance programs in line with budgetary constraints and funding limitations, Bridge Management Systems (BMSs) are indispensable for state Departments of Transportation (DOTs). However, although BMSs have been created and developed for more than 20 years, they still have some limitations: 1) limited capability to share and retrieve data information electrically among DOT divisions; 2) limited web-based application; 3) flat graphic or unfriendly user interface; 4) limited data types, for example, exiting NBI database has long been lacking of any imagery data such as remote sensing data, photos or any public volunteered information [3]; and 5) due to the 1-year or 2-year cycle of inspection and the discrete bridge locations, it is appreciably difficult for DOTs to maintain real-time observations of these bridges.

To address these issues and fulfill the SPTC's mission on climate adaptive transportation and freight infrastructure, this research project developed and implemented a web GIS-based bridge management system, which allows for advanced geospatial visualization and potential data integration on a centralized on-line platform. The specific objectives of this project are: 1) to provide a comprehensive review of current BMS development activities; 2) to identify available bridge-related data sources at the state DOT, which enable the further data integration needed for a variety of analytical purposes; 3) to build a more realistic model to represent the deterioration of bridge components by using a semi-Markov transition process. The semi-Markovian transition probabilities will be derived directly by accessing and analyzing the NBI database; and 4) to develop a web GIS-based bridge management system, which allows advanced geospatial visualization and potential data integration on a centralized cloud platform. The pertinent bridge maintenance data includes text, images, engineering documents, citizen reports and remote sensing data.

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2. Literature Review

2.1 Current Bridge Conditions

Each year, the FHWA releases raw data gathered over the course of 12 months as part of its National Bridge Inventory (NBI) Database. After analyzing the 2015 NBI raw data, the American Road & Transportation Builders Association (ARTBA) released a state-by-state breakdown of the number of structurally deficient bridges in the United States. In all, 58,495 bridges out of the 629,539 bridges in the U.S. are currently rated as structurally deficient. This equates to 9.6 percent of the bridge stock in the nation [1]. The American Society of Civil Engineers (ASCE) estimated that the cost of bringing America's infrastructure to a state of good repair by 2020 at $3.6 trillion, of which only about 55 percent has been committed [2]. Increasing concerns about allocating the limited funds to maximize bridge maintenance efficiency have been expressed at all levels of transportation agencies including federal, state and local governments; this concern translates to a strong demand for more efficient and effective bridge inspection and management technology.

2.2 Bridge Inspection

During the bridge construction boom of the 1950s and 1960s, little emphasis was placed on safety inspection and maintenance of bridges [4]. However, the collapse of Silver Bridge at Point Pleasant, West Virginia changed this; 46 people were killed in this tragic event. The collapse aroused national interest in the safety inspection and maintenance of bridges. The U. S. Congress was prompted to add a section to the "Federal Highway Act of 1968," requiring the Secretary of Transportation to establish a national bridge inspection standard. The Secretary was also required to develop a program to train bridge inspectors.

In 1971, the National Bridge Inspection Standards (NBIS) came into being and national policies were established for bridge inspection and maintenance. The FHWA made considerable effort on the development of NBI, which helps bridge inspectors inspect and evaluate the national bridges accurately. The NBI database contains a great deal of information related to bridge performance, including such parameters as material types, roadway types, traffic volumes (or ADT), bridge ages, and more. During mostly biannual inspections, bridges are assigned a condition rating from 0 to 9 based on field inspection and written comments. A rate of 9 indicates the best condition or a relatively new bridge, while 0 stands for the worst condition, "the failed condition" or being "out of service." To unify recording and coding of bridge information, the FHWA coding guide suggested a bridge rating for three main elements of a bridge: 1) the deck; 2) the superstructure; and 3) the substructure [5] [6]. If the rating score of any of these three elements is below 4 or less, the bridge is categorized as structurally deficient by federal standards. These structurally deficient bridges arouse more attention from bridge engineers regarding needs assessment and budget allocation.

2.3 Bridge Management System

Bridge Management Systems (BMSs) are a means of managing information of bridges to support decision-making that assures their long-term health and to formulate maintenance programs in line with budgetary constraints and funding limitations [7].
The major tasks in bridge management are: (1) collection of inventory data, (2) inspection, (3) assessment of condition and strength, (4) decisions about repair, strengthening or replacement, and (5) prioritization of the allocation of funds. To fulfill these tasks, BMSs include four basic components: data storage, cost and deterioration models, optimization and analysis models, and updating functions [8] [9]. The core part of a BMS is a database built of information obtained from regular inspection and maintenance activities. Bridge database management includes collection, updating, integration, and archiving of the following information: (1) bridge general information (location, name, type, load capacity, etc.), (2) design information and physical properties of the elements, (3) inventory data, (4) regular inspection records, (5) condition and strength assessment reports, (6) repair and maintenance records, and (7) cost records. For a BMS to be effective, it must include realistic bridge deterioration models in order to predict the consequences of different possible corrective actions that are available to decision-makers in highway agencies. Also, it must be able to provide data visualization of the bridge information for clear interpretation of bridge conditions. A strategic

maintenance decision-making support system should be included as well, which can help bridge engineers make effective planning and maintenance program.

In the U.S., with the passage of the Inter-modal Surface Transportation Efficiency Act of 1991, state highway agencies were required to implement infrastructure management systems in five broad areas by the year 1995, namely, highway pavement of federal-aid highways, bridges on and off federal-aid highways, highway safety, traffic congestion, and public transportation facilities and equipment. Although various state departments of transportation (DOT) as well as the US DOT had developed some of these systems previously, this legislation provided the impetus for the adoption of bridge management systems (BMS). Since then a significant number of BMSs have been proposed or developed by state DOTs (such as North Carolina, Pennsylvania, Alabama, Indiana, Washington, Connecticut, Texas, Iowa, and South Carolina).

A comprehensive literature review on design, construction, operation, and maintenance of bridges was conducted for 25 existing bridge management systems (BMSs). The selected 25 BMSs from 18 countries manage approximately 1,000,000 objects. The topics of our review are consistent with two previous review reports issued by International Association of Bridge Maintenance and Safety [10, 11], including:

- Basic general information: general information on BMSs.
- Basic IT information: information technology aspects of BMSs.
- Basic inventory information: information on the infrastructure objects such as structure types, location information, loading information, use information, etc.
- Inspection information: information about inspections.
- Intervention information: information about maintenance and preservation activities such as repair, rehabilitation, and reconstruction.
- Prediction information: information predicted by BMSs, such as change in physical condition and performance indicators due to deterioration and the execution of interventions.
- Use information: information on the special ways that the BMSs are used.
- Operational information: information on how the data are collected, and how the quality is assured.

In Table 1, the 25 selected BMSs are listed with their original countries and the year for the first and current versions. The Bridge column shows the number of bridge objects for each BMS, which ranges from 0 (SZOK) to 500,000 (AASHTO). The total number of bridge objects managed by them is 667,112. Note that the Total field represents the total number of objects including bridges, culverts, tunnels, retaining structures, and others in the BMSs. Among the selected 25 BMSs, three important aspects are summarized as follows:

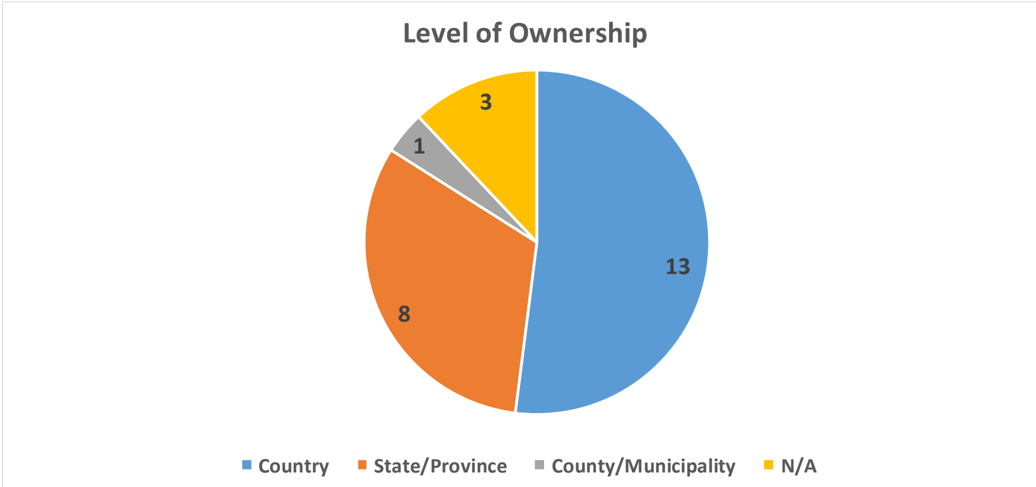
- Level of ownership: the ownership is divided into three levels: level, state/province level, and county/municipality level. About half of the objects are owned at the country level, and eight systems are at the state/province level (as shown in Figure 2(a)).

- Cost information: the cost information includes inspection cost, intervention cost, traffic delay cost, accident cost, and environmental cost. Figure 2(b) shows that most of the BMSs (24 BMSs) can handle intervention information, while only six BMSs could handle inspection costs.

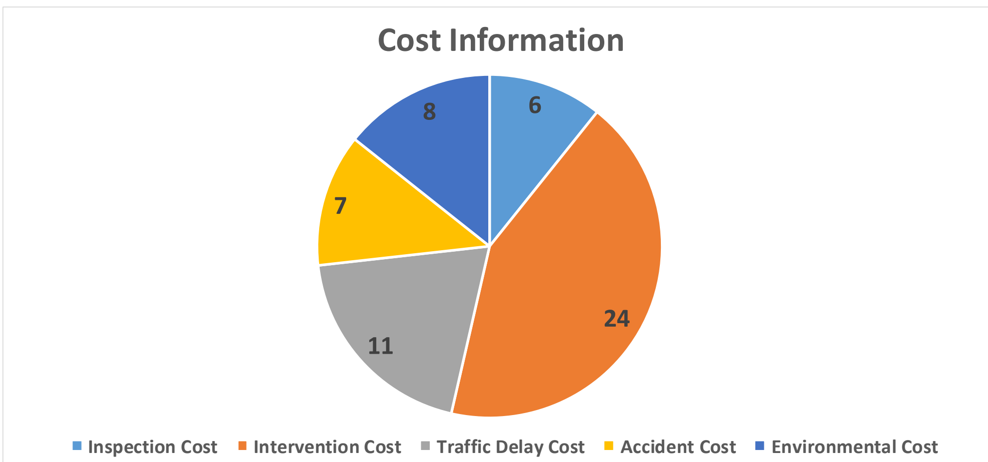
- Predictive capabilities: the predictive capabilities refer to the prediction of deterioration (e.g., changes in physical condition and performance indicators), effects of intervention/improvement (e.g., changes in physical condition and performance indicators due to interventions), optimal intervention strategies (e.g., period of time analyzed and cost types), and work program (e.g., period of time analyzed, cost types and budget constraints). Figure 2(c) shows that 21 BMSs are reported to provide work program; 19 BMSs can predict deterioration and determine the optimal intervention strategies; 18 BMSs are capable of predicting improvement.

Table 1 Reviewed Bridge Management Systems [10, 11]

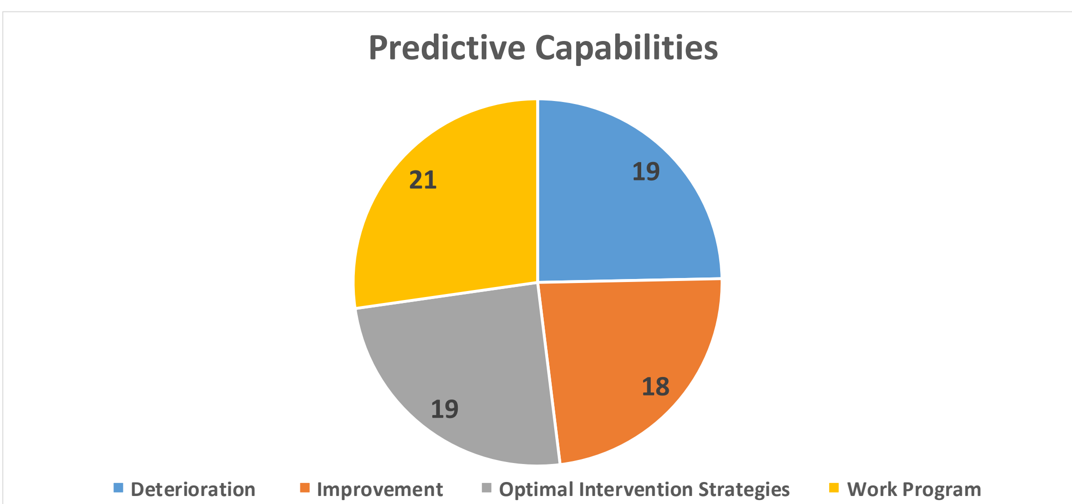
No.	Bridge Management Systems	Country	First Version	Current Version	Bridges	Total
1	MRWA Bridge Management System (MRWA)	Australia	2011	2013	2815	2898
2	NSW Bridge Management System (NSW)	Australia	1996	2013	2702	6143
3	Ontario Bridge Management System (OBMS)	Canada	2002	2012	373	373
4	Quebec Bridge Management System (QBMS)	Canada	2001	2009	102	355
5	EBMS (EBMS)	Canada	2006	2011	2800	5400
6	PEI BMS (PEI BMS)	Canada	2006	2011	800	1200
7	GNWT Bridge Management System (GNWT)	Canada	2011	2013	8700	11100
8	DANBRO Bridge Management System (DANBRO)	Denmark	1975	2010	2250	2250
9	The Finnish Bridge Management System (FBMS)	Finland	1990	2010	13787	17065
10	Bauwerk Management System (GBMS)	Germany	N/A	N/A	10000	10000
11	Eirspan (Eirspan)	Ireland	2001	2008	2997	2997
12	APT-BMS (APT-BMS)	Italy	2004	2013	1108	1953
13	BMS@RPI (RPIBMS)	Japan	2006	2009	4239	5018
14	Korea Road Maintenance Business System (KRMBS)	Korea	2003	2012	6192	6192
15	Lat Brutus (Lat Brutus)	Latvia	2002	2004	934	1979
16	DISK (DISK)	Netherlands	1985	2006	3836	5591
17	BRUTUS (BRUTUS)	Norway	1995	2013	11500	20080
18	SMOK (SMOK)	Poland	1997	2007	7902	33250
19	SZOK (SZOK)	Poland	2001	2010	0	0
20	SGP (SGP)	Spain	2005	2013	24534	40045
21	Bridge and Tunnel Management System (BaTMan)	Sweden	1987	2011	33000	45790
22	KUBA (KUBA)	Switzerland	1991	2014	12574	31313
23	ABIMS (ABIMS)	United States	1994	1994	500000	750908
24	AASHTOWare (AASHTO)	United States	1992	2014	9728	15842
25	Bridgeman (Bridgeman)	Vietnam	2001	2010	4239	4239



(a)



(b)



(c)

Figure 2 Characteristics of Reviewed Bridge Management Systems

2.4 Limitations of Existing BMSs

According to our literature review on bridge inspection and management, several limitations of existing BMSs are:

- Existing bridge inspection is a unidirectional multi-step process that may take months to accomplish, as shown in Figure 3. The entire process includes inspection planning and preparing inspection, conducting on-site inspection, completing inspection forms, inputting the inspection data, and storing the data into state bridge inventory. The process may last several days for state agency and 180 days for local agency. After further processing by state DOT staff, the final bridge inventory data are then submitted to the USDOT for updating the NBI database annually. The prolonged time period for data collection in NBI reflects that the bridge inspection process has not benefited from the advancement of modern information technology.

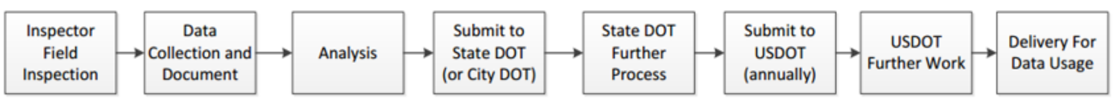


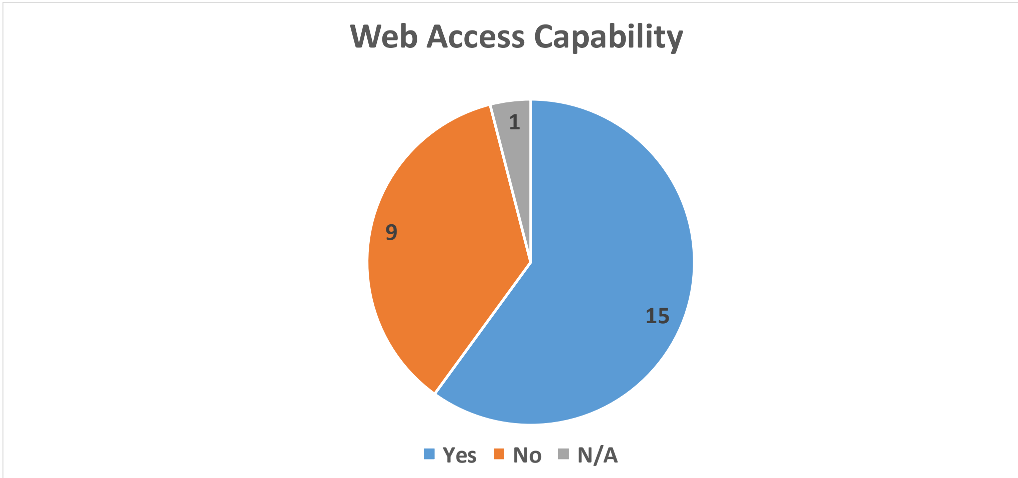
Figure 3 Existing Bridge Inspection Process

- Currently, State DOTs lack a comprehensive and centralized BMS to integrate different systems that are not interlinked to store different bridge information. These systems are usually stored and maintained by different DOT divisions. For example, various information systems at TxDOT contain data that pertain to the design, construction, operation, and maintenance of bridges, including Design and Construction Information System (DCIS), Maintenance Management Information System (MMIS), Bridge Inventory, Inspection, and Appraisal System (BRINSAP), PonTex, Pontis, Financial Information Management System (FIMS), Texas Permit Routing Optimization System (TxPROS), Permanent Structure Number (PSN) application, and Bridge Shop Plan. Because there is no capacity to retrieve bridge information electronically encompassing these systems, information essential to the optimal management of bridges is not readily available to DOT engineers and decision makers. Additionally, information on bridge-related maintenance expenditures is extremely limited to the most basic of categories, and more detailed cost information is effectively nonexistent with the current system in Texas.

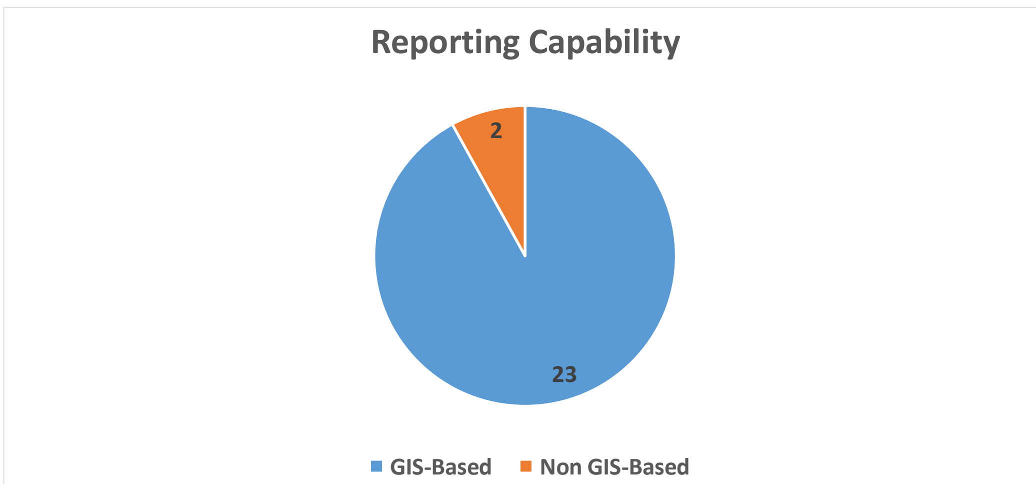
- For a BMS to be effective, it must include realistic bridge deterioration models to predict the consequences of different possible corrective actions available to decision-makers in highway agencies. Currently, major BMSs use a traditional Markovian process to predict the deterioration of a bridge. However, in real practice, a bridge deterioration process in which sojourn (or waiting) times in any given state are time-dependent distributed random variables cannot be captured by a discrete time Markov chain. In this regard, a semi-Markov chain with various transition probability matrices can relax this limitation and is more suitable to capture the bridge's real degradation process. A semi-Markov process is a class of stochastic processes that moves from one state to another, with the successive states visited forming a Markov chain. The process stays in a particular state for a random length of time, and its distribution depends on the state and on the next state to be visited [12]. In the new proposed BSM, the semi-Markov transition matrix will be derived from the NBI database.

- Based on the reviewed BMSs, some additional weaknesses are:

  - Limited Web-based Application: Among 25 selected BMSs, only 15 have web access to the systems. Other systems (about 40%) do not have such function or the information was not provided (as shown in Figure 4(a)).
  - Limited Reporting and Visualization Capability: Only two (APTBMS and KUBA BMSs) out of 25 systems have GIS-based reporting and visualization functions (as shown in Figure 4(b)). Most of the BMSs report the data using text, tabular, and photos, while GIS-based reporting function can provide user-friendly interfaces for geospatial visualization.
  - Limited Data Collection Capability: Most of the current BMSs still use a manual input approach for collecting and entering data to the system. Only two systems (BRUTUS and DISK BMSs) can collect data via web services (shown as in Figure 4(c)).



(a)



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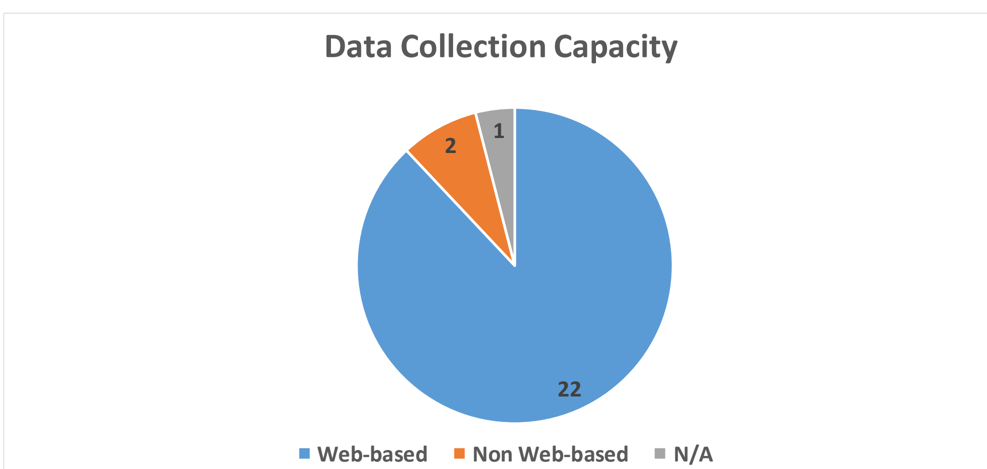

(c)

Figure 4 Limitations of Current Bridge Management Systems

3. Bridge Performance Prediction Model

Bridge performance prediction model is the core component of a BMS. In this project, the research team developed a semi-Markov process-based model to predict bridge performance by using the NBI dataset. The details of the model is discussed in detail in this section.

3.1 The limitations of current bridge performance models

The researchers first investigated the existing models and divided them into three general groups, despite their substantial differences in detail:

- The first group establishes empirical relationships between the factors affecting bridge deterioration and the measures of a bridge's condition. The output of such models is expressed by deterministic values, and no probabilities are involved. These deterministic models can be categorized as using straight-line extrapolation, regression, and curve-fitting methods.

- The second group describes the specific deterioration mechanisms of particular bridge components and focuses on the reliability of bridges with respect to strength limit states (load versus resistance). The deterioration models are dependent on deterministic mathematical formulas or probabilistic analyses using the Monte Carlo Simulation (MCS).

- The third group considers the bridge deterioration process stochastic in nature and creates probabilistic forecasting models. The state-of-the-art stochastic model has been proposed mainly based on the classic Markov chain theory.

However, these existing deterioration models still have some noticeable drawbacks, including:

- Failure to incorporate multiple relevant factors that impact the bridge deterioration process, such as climate, traffic density, material property, bridge route type, etc.;
- Lack of the ability to predict the performance of a bridge that has undergone repair or maintenance activities;
- Failure to optimize maintenance strategies from the viewpoints of economy and

repair efficacy;

- Assumption of discrete transition time intervals, a constant bridge population, or stationary transition probabilities in some of the Markov-based models.

To overcome these limitations, a life-cycle bridge performance model using a semi-Markov process was developed.

3.2 The Proposed Semi-Markov bridge performance model

In a traditional Markov process, the future states of the process depend only on the current states. The rates of transition from one state to another remain constant throughout. In other words, the probability transition matrices are constant. As used in PONTIS, only one transition matrix is used on the whole life span of the bridge, and does not consider the impact of bridge age and many other factors on the bridge performance apparently.

However, bridge deterioration is a complicated process affected by various factors, including aging, construction material, environmental conditions, traffic density, and more. In real practice, a bridge deterioration process in which sojourn (or waiting) times in any given state are time-dependent distributed random variables cannot be captured by a discrete time Markov chain (or the traditional Markov process). In this regard, a semi-Markov chain with various transition probability matrices can relax this limitation and is more suitable to capture the bridge's real degradation process. A semi-Markov process is a class of stochastic processes that moves from one state to another, with the successive states visited forming a Markov chain. The process stays in a particular state for a random length of time, and its distribution depends on that state and on the next state to be visited. In the semi-Markov process, the state transition has the Markov property and the holding time in each state is assumed to follow a probability distribution (according to the literature, the Weibull distribution is the suitable candidate).

The proposed model, assuming that it is generally applicable and by including these variables, could use bridge-specific information to realistically model the service life deterioration behavior of bridges in a specific environment. Although only steel bridges over the Texas local routes were analyzed to validate the proposed model, the model is generally applicable to other types of bridges constructed with other materials. The proposed model is also applicable to optimize the maintenance of bridge components, i.e., decks, superstructures, and substructures. The algorithm of the proposed model is shown as Figure 5, and is also presented in the authors' work [13].

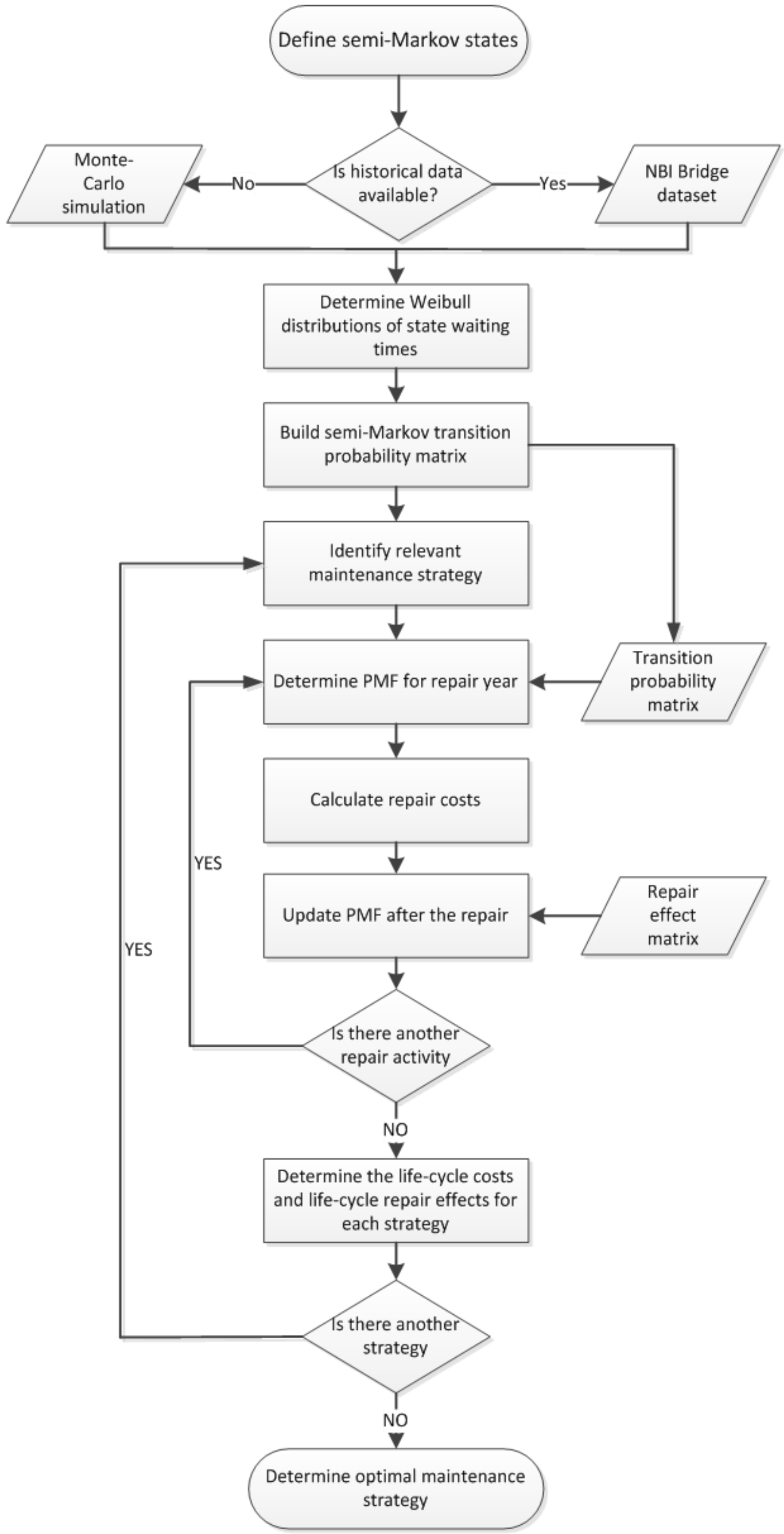

Figure 5 The flowchart of the proposed bridge performance model

The records in the NBI database were used to build the proposed model and to validate the model as well. The NBI database contains a great deal of information related to bridge performance, including such parameters as material types, roadway types, traffic volumes (or ADT), bridge ages, and more. The performance ratings are assigned numerically by inspectors during mostly biannual inspections. After examining the rating factors carefully, the research team selected Sufficiency Rating (SR), a method of evaluating highway bridges by calculating four separate factors (structural evaluation, functional obsolescence, serviceability and special reductions) to obtain a numeric value (percentage) that is indicative of bridge sufficiency to remain in service, as the main performance indicator in this study (FHWA 1995). SR is essentially a comprehensive rating of a bridge's fitness for the duty it performs based on factors derived from over 20 NBI data fields, including fields that describe its structural evaluation, functional obsolescence, and its essentiality to the public. One hundred percent represents an entirely sufficient bridge, and zero percent represents an entirely insufficient or deficient bridge. In the NBI dataset, the records for each bridge include over one hundred pieces of information, each identified by an item number. For example, Item 029 presents the average daily traffic, Item 058 indicates the rating of deck conditions, and Item 043A groups bridges by material types.

To build and validate the proposed bridge performance model, we designed a case study for the purpose of demonstration, in which the 2012 NBI dataset for Texas bridges was used. It should be noted that the deterioration process (and accordingly, the Markov transition matrix) is greatly affected by the service or site condition to which the bridge is exposed. Thus, the following actions were taken for extracting information from the 2012 NBI records for Texas and filtering the bridges into six subgroups, as shown in Table 2:

- Bridges that have undergone reconstruction or rehabilitation were removed from the inventory.
- Bridges are filtered out by Functional Classification of Inventory Route (NBI Item 026). Only Interstate (codes 01 and 11) and Local (codes 09 and 19) bridges were considered in the analyses.
- Only common structural materials were considered, excluding wood, masonry, or aluminum structures from the study. For each route type, bridges were divided into three subgroups due to the main structural material type: Concrete (NBI Item

043A codes 01 and 02), Steel (NBI Item 043A codes 03 and 04), and Pre-stressed Concrete (NBI Item 043A codes 05 and 06). It should be noted that a bridge may be categorized in the NBI as steel, concrete, or timber, but not all components are necessarily constructed of that material.

- Average Daily Traffic (NBI Item 029, ADT) was considered relevant due to the direct effects of traffic loading on deterioration as well as the likely relationship between the amount of deicing salt used (harmful chloride exposure) and traffic volume. For the Interstate route type, bridges under heavy traffic conditions (ADT > =5,000 vehicles per day (vpd)) were included, representing the most severe service condition. For the local route type, only bridges with light traffic (ADT < =5,000 vpd) were retained.

- Sufficiency Rating (SR) was used to evaluate the bridge condition numerically, ranging from a low of 0 percent to a high of 100 percent. A rating of 90 percent or higher indicates excellent condition, and a rating of 20 percent or lower indicates a critical condition or imminent failure condition. Other ratings indicate: poor condition, fair condition, satisfactory or good condition。

Table 2 The bridges selected from the 2012 NBI dataset for Texas

Material Type	Interstate Bridges	Local Bridges
ADT	Heavy Traffic (>= 5000)	Light Traffic (<=5000)
Truck Percentage	> 10%	< 10%
Concrete Bridge Group	1,388 (48%)	1,209 (53%)
Steel Bridge Group	252 (8.7%)	389 (17%)
Prestressed Concrete Bridge Group	1,248 (43.3%)	682 (30%)
Total	2,888 (100%)	2,280 (100%)

Figure 6 and Figure 7 depict regression curves for the performance and SR values of selected interstate and local bridges, respectively. The life-cycle performance curves, as depicted in these figures, can be characterized as follows:

- The potential of the bridge deterioration process (or state transition matrix) is closely related to bridge types, construction materials, and service conditions. Once the category of a bridge is known, its transition matrix of degeneration can then be determined correspondingly.

- Regarding interstate bridges, steel and pre-stressed concrete perform better than concrete when the bridge is less than 50 years old. However, once this age is passed, the deterioration of these materials accelerates. Steel bridges have the fastest deterioration rate of the three types, while concrete bridges typically provide the most consistent performance during their life cycles.

- Regarding local bridges, concrete bridges present the best performance and pre-stressed concrete bridges have the second best, while steel bridges still deteriorate at the fastest rate, which is the same trend observed from interstate bridges.

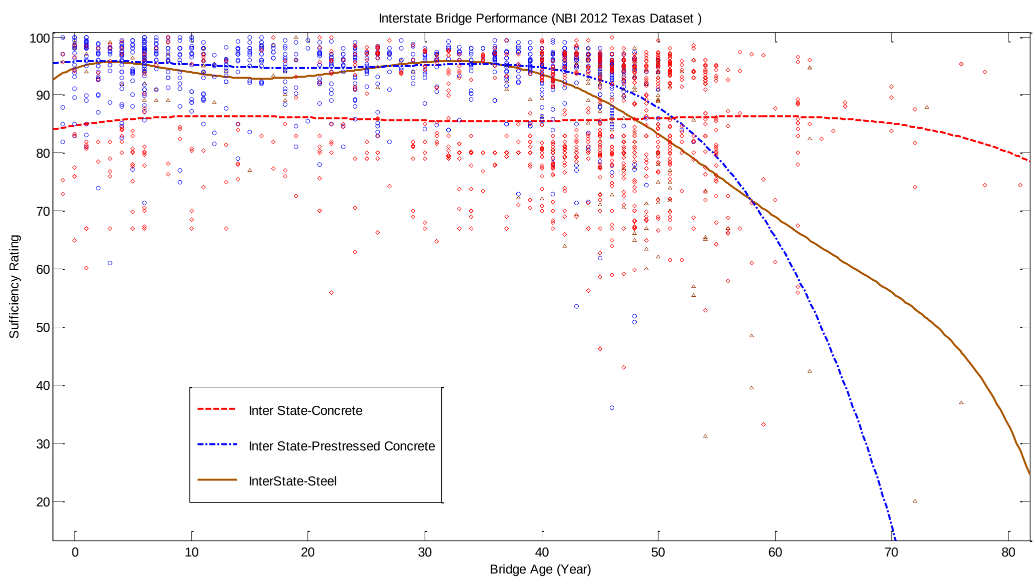

Figure 6 The Performance of Interstate Bridges based on the NBI 2012 Dataset for Texas

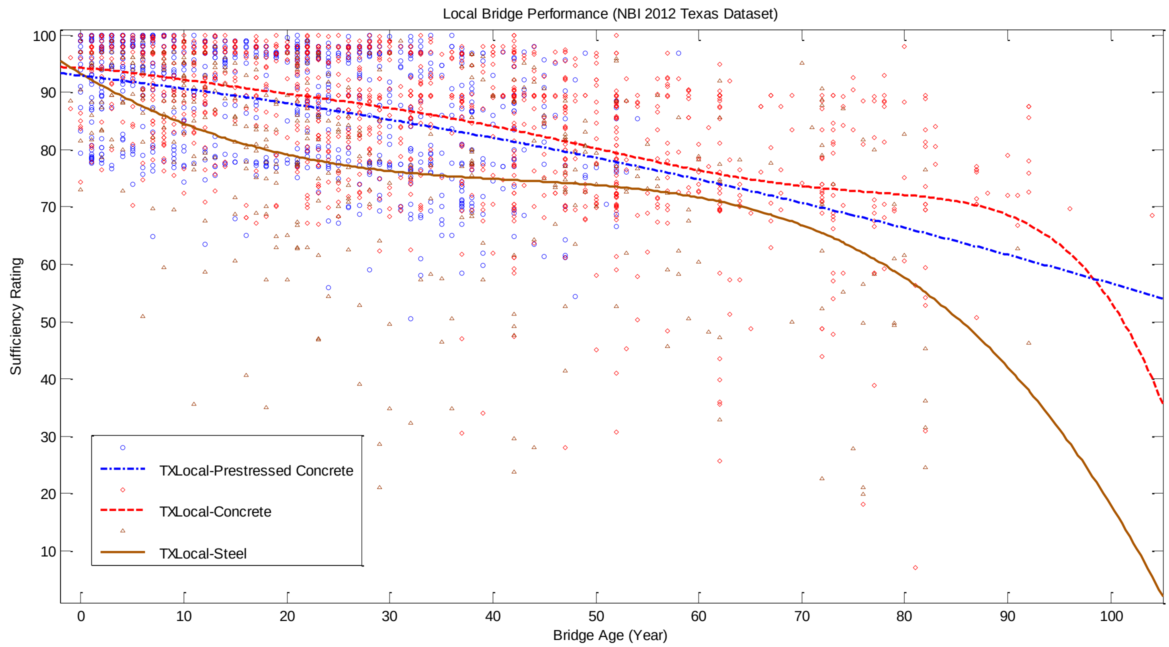

Figure 7 The performance of Local bridges based on the NBI 2012 Dataset for Texas

The bridge performance from the proposed semi-Markov model was compared with the real performance from the NBI 2012 Texas dataset, as shown in Figure 8.

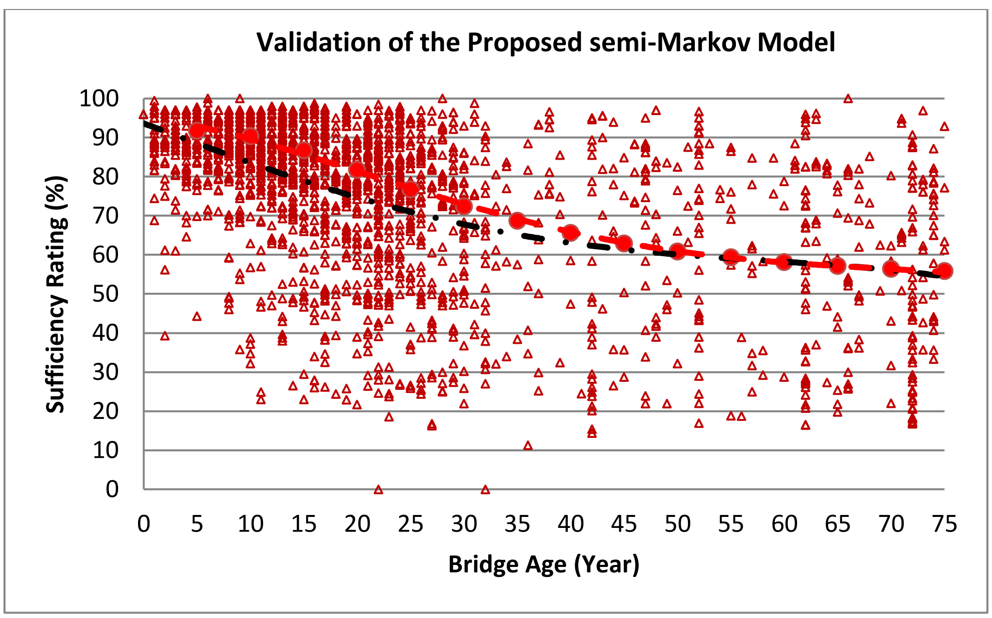

Figure 8 Validation of the Proposed Deterioration Model and the 2012 NBI Historical Records for Texas

Based on the proposed model, we can also optimize maintenance strategies and compare them based on both repair effects and life-cycle costs, as shown in Figure 9.

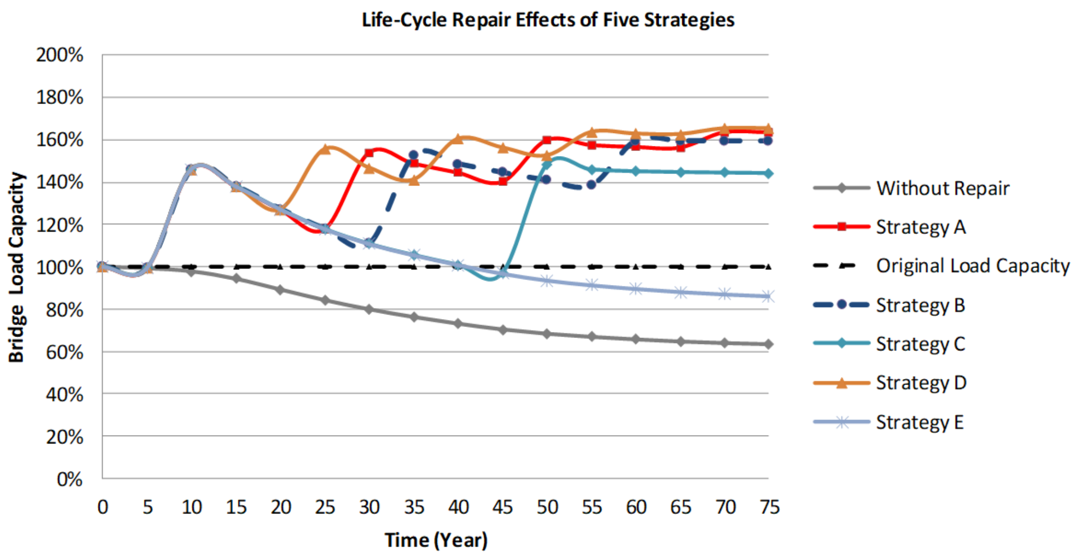

Figure 9 Comparing different repair strategies based on the proposed model

4 The Developed Bridge Management System

The research team has extensive experience in the application of Esri™ technology-based ArcGIS Online to develop a map-centric content management system that stores and integrates data, delivers visualized outputs, and manages user access and security [14-18]. The developed BMS is designed as a bi-level platform, in which the upper level manages the overall bridge network based on two-dimensional (2D) vectors or images, while the lower level handles three-dimensional (3D) spatial information and real time data streams for monitoring the health of individual bridges. One major development of this project was an open source BMS prototype that create custom applications, provide a platform for integrating GIS with other business systems, and enable cross-organizational collaboration. The prototype aims to provide an open-source architecture for the public. Its architecture and codes will be open to end users and thus can be easily customized by any transportation agencies for their bridge management needs. The main interface of the proposed BMS is shown in Figure 10.

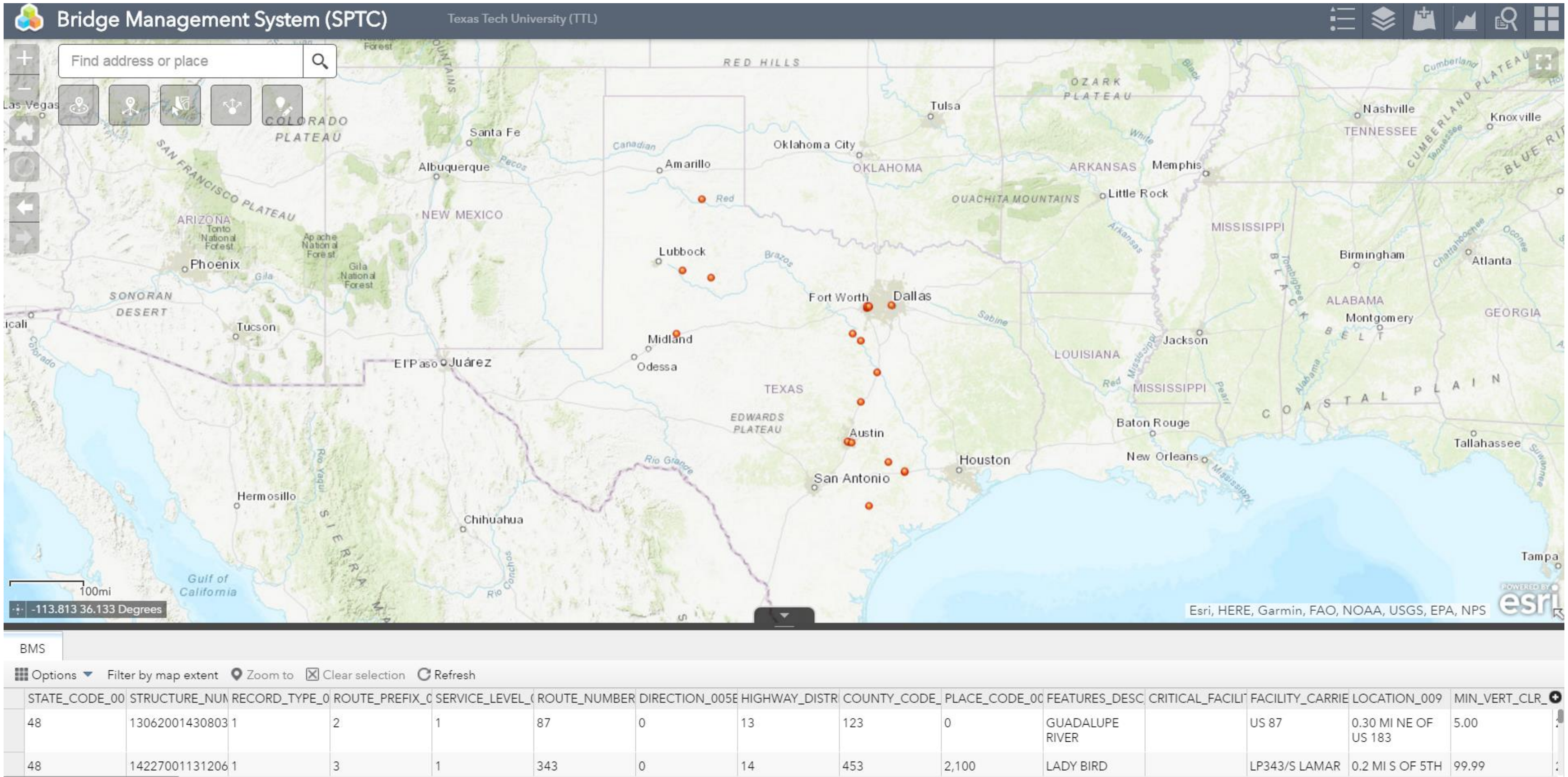

Figure 10 The developed web-GIS based bridge management system

4.1 The Bridge Geo-Database

The researchers have built a bridge database based on the 2016 National Bridge Inventory (NBI) dataset. The 2016 NBI database contains over 100 pieces of information related to the recorded bridges, including such parameters as performance ratings, material types, roadway types, traffic volumes (or ADT), bridge ages, and more. For example, Item 029 presents the average daily traffic, Item 058 indicates the rating of deck conditions, and Item 043A groups bridges by material types. Also in the NBI dataset, bridge performance ratings are assigned numerically by inspectors during mostly biannual inspections. After examining the rating factors carefully, the research team selected Sufficiency Rating (SR), a method of evaluating highway bridges by calculating four separate factors (structural evaluation, functional obsolescence, serviceability and special reductions) to obtain a numeric value (i.e., percentage) that is indicative of bridge sufficiency to remain in service, as the main bridge performance indicator in this project. SR is essentially a comprehensive rating of a bridge's fitness for the duty it performs based on factors derived from over 20 NBI data fields, including fields that describe its structural evaluation, functional obsolescence, and its essentiality to the public. One hundred percent represents an entirely sufficient bridge, and zero percent represents an entirely insufficient or deficient bridge. Due to the scope of this project, we only focused on the NBI bridges in Texas, as shown in Figure 11.

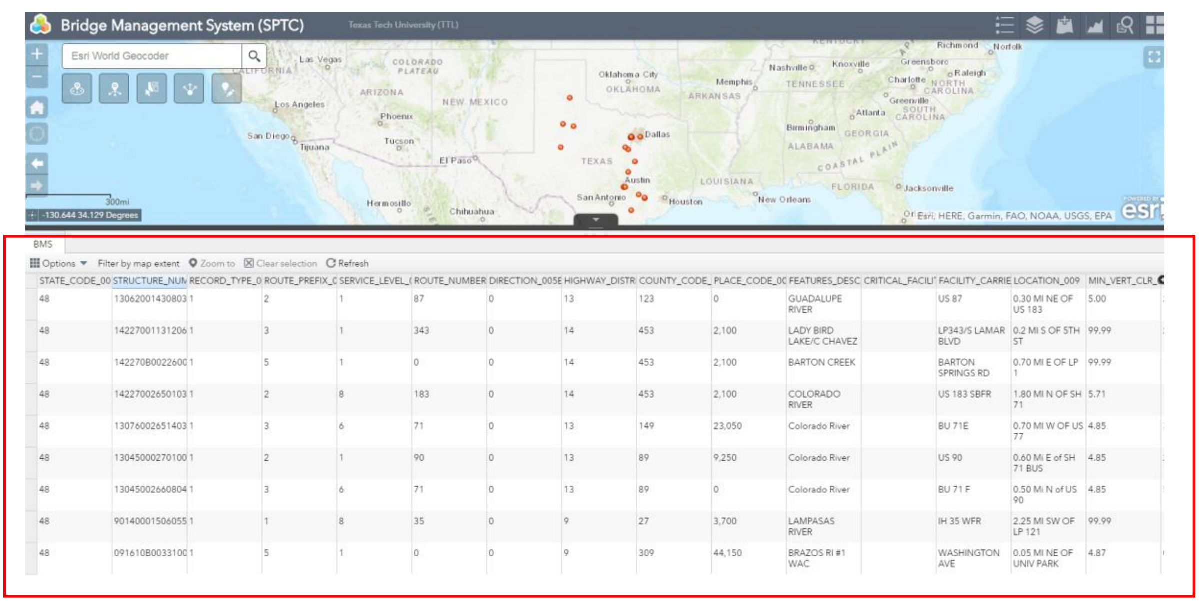

Figure 11 The Bridge Geo-Database from the 2016 NBI Texas Database

4.2 The Proposed BMS

The proposed BMS has major functions such as a web GIS-based visualization interface, a geodatabase of selected sample bridges, and many powerful widgets. Note that the functionality of the proposed BMS is realized by widgets. In the next sub-sections, the major widgets of the BMS are elaborated one by one.

4.2.1 Base Map

The Base Map widget presents a gallery of base maps and allows the user to select one from the gallery as the base map for the BMS, as shown in Figure 12. There are 12 default base maps for selection, such as “Streets,” “Imagery,” “Topographic,” among others.

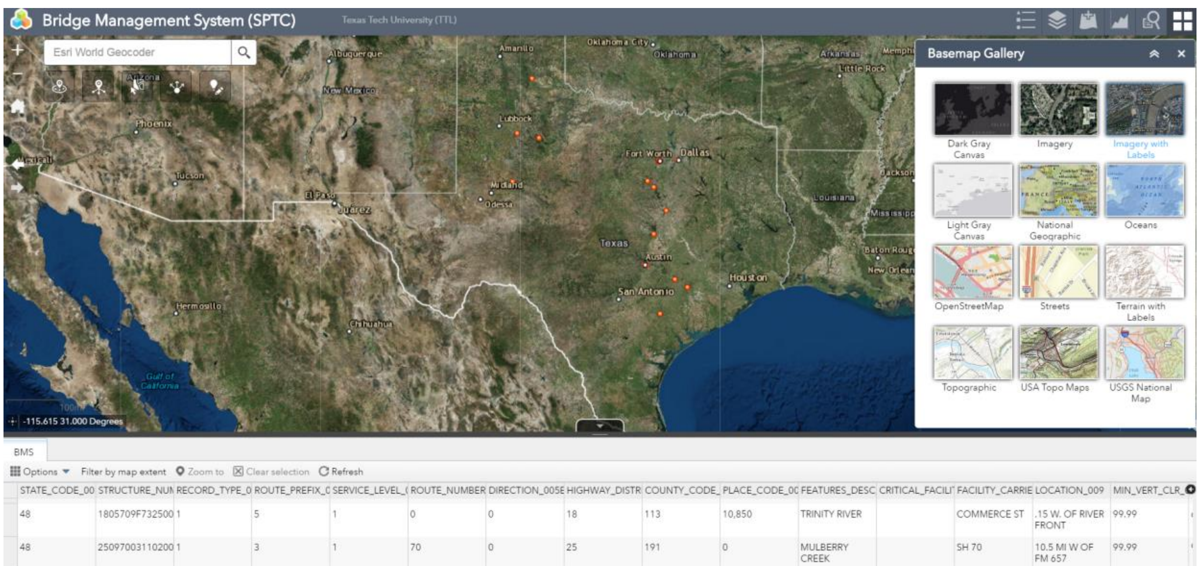

Figure 12 The Base Map Widget

4.2.2 Query

The Query widget allows the user to retrieve bridge information from the NBI geo-database by executing a predefined query, as shown in Figure 13. The Query widget serves as a query builder during configuration, allowing you to define the query by specifying source data and filters, and displaying fields in query results. Each query works with a single layer. However, you can define multiple queries for a single app, and data layers can be from multiple sources.

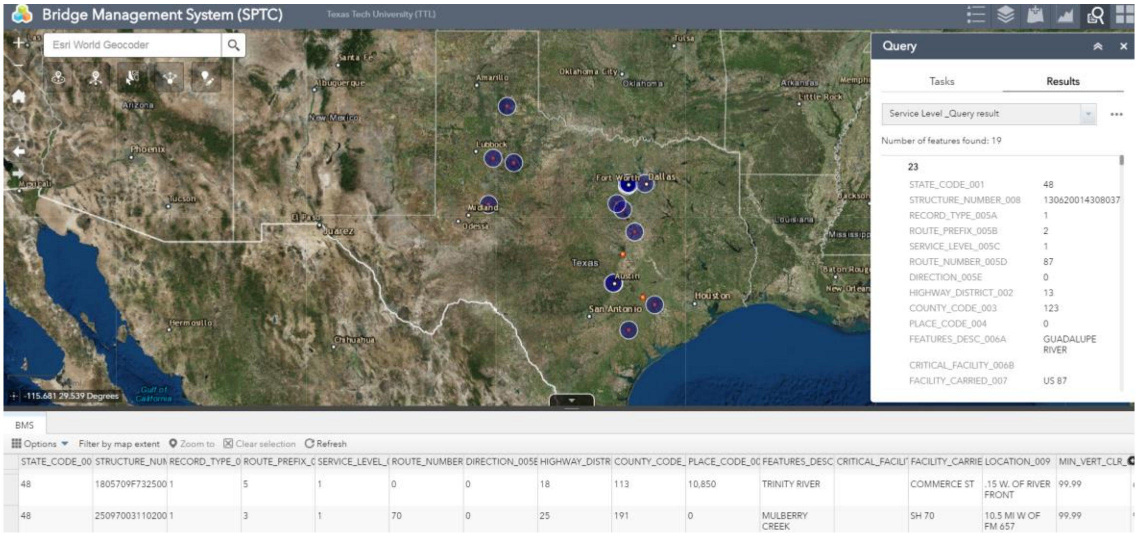

Figure 13 The Query Widget

4.2.3 Add Data

The Add Data widget enables the user to add data to the BMS in a more flexible way. By using this widget, the user can temporarily add more bridge data layers to and remove these layers from the BMS conveniently. The data can be uploaded in the following formats: ArcGIS Shape File, CSV, KML, CPX, and GeoJSON. The interface of this widget is shown in Figure 14.

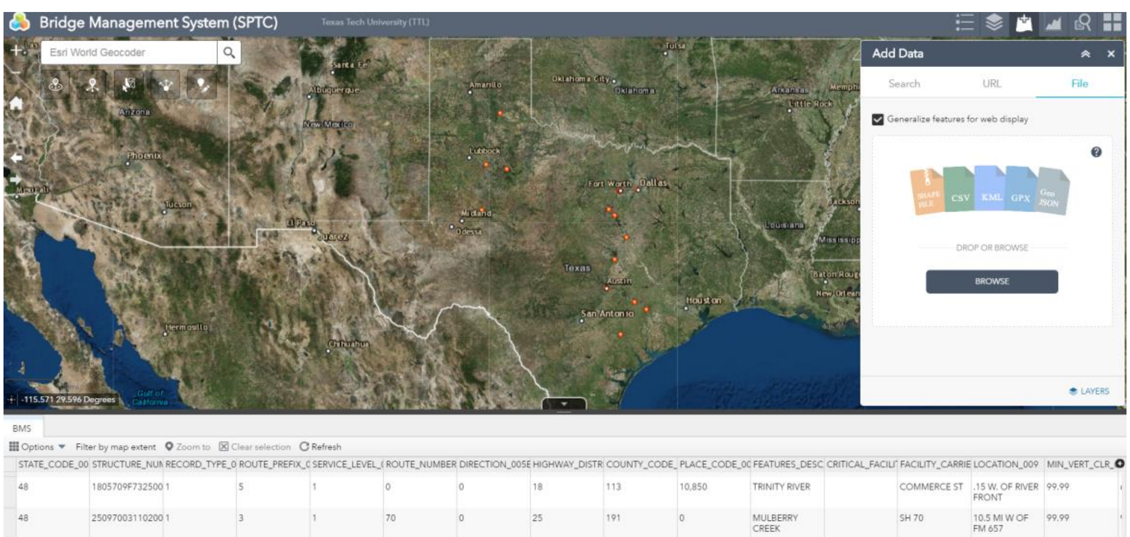

Figure 14 The Add Data Widget

4.2.4 Smart Editor

The Smart Editor widget enables the user to edit the bridge information directly in the geo-database, as shown in Figure 15. The user can configure descriptions in the tables and the layers, create, update, and delete related records, and view pop-ups from other data in the map while in editing mode. After the user finishes the editing, the related bridge information in the geo-database will be also updated automatically.

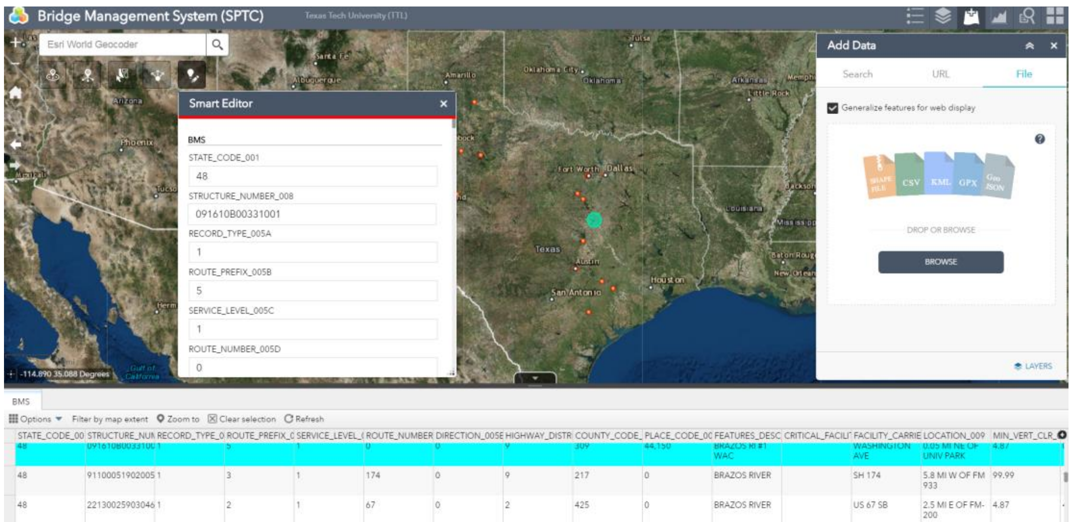

Figure 15 The Smart Editor Widget

4.2.5 Chart

The Chart widget displays quantitative attributes from an operational layer as a graphical representation of data. This widget allows end users to observe possible patterns and trends out of bridge raw data, as shown in Figure 16.

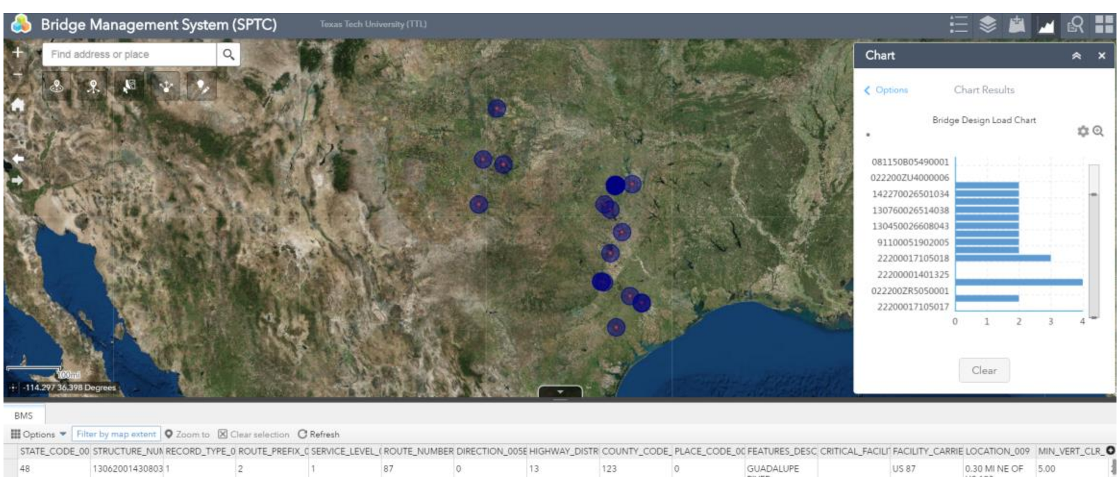

Figure 16 The Chart Widget

4.3 The Proposed BMS 3D Component

As mentioned previously, the developed BMS is designed as a bi-level platform, in which the upper level manages the overall bridge network based on two-dimensional (2D) vectors or images, while the lower level handles three-dimensional (3D) spatial information and real time data streams for monitoring the health of individual bridges (as shown in Figure 17 and Figure 18). Note that we used ArcGIS Web scenes to build a bridge in the 3D environment. As defined by Esri™, a scene is symbolized in 3D geospatial content that allows the user to visualize and analyze geographic information in an intuitive and interactive 3D environment. A scene is made of the following components:

- Layers—2D and 3D data, such as scientific, urban planning, or environmental data with styles and configurations. In this case, Layers will contain the spatial and other relevant information of bridges.
- Basemap—A basemap provides a background of geographical context for the content in your scene.
- Ground—The terrain with elevation data that can be turned on and off.

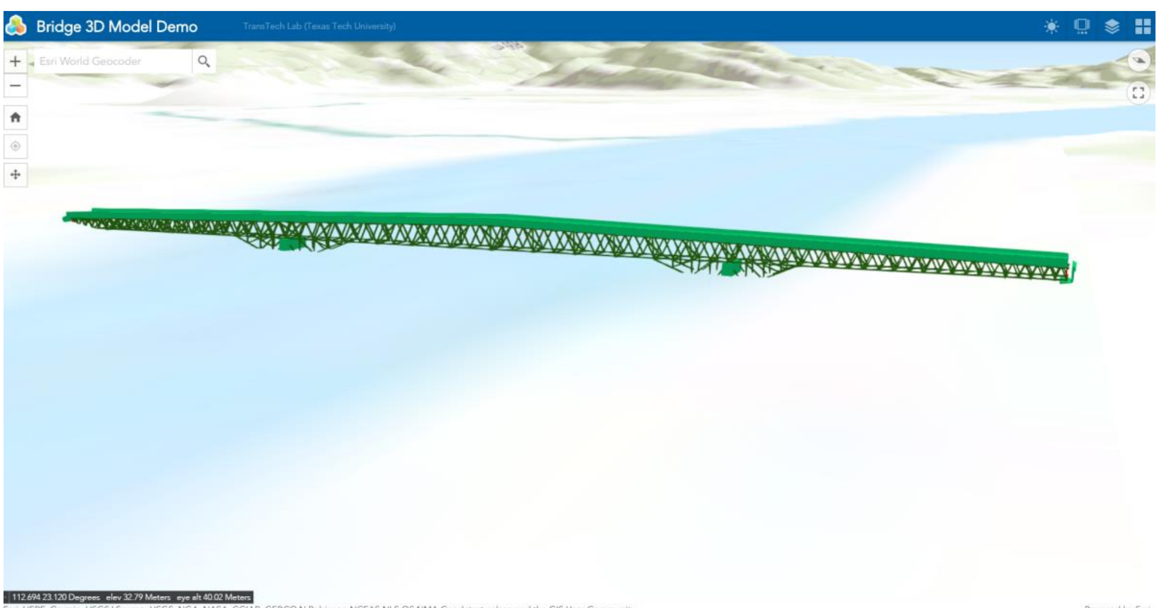

Figure 17 The developed 3D BMS component

Figure 18 is a great example of how bridge managers can use the developed 3D BMS component as a tool for their bridge management. They can see the highlights of the sample bridge and interact with it under the different scenarios in 3D surroundings. For example, the user can quickly grasp the bridge features, such as slabs, beams, decks, and foundations. Because the developed tool is such a great 3D visualization platform, the user can easily explore the bridge through 3D visualization scenarios, and immediately communicate their ideas with the stakeholder and the public.

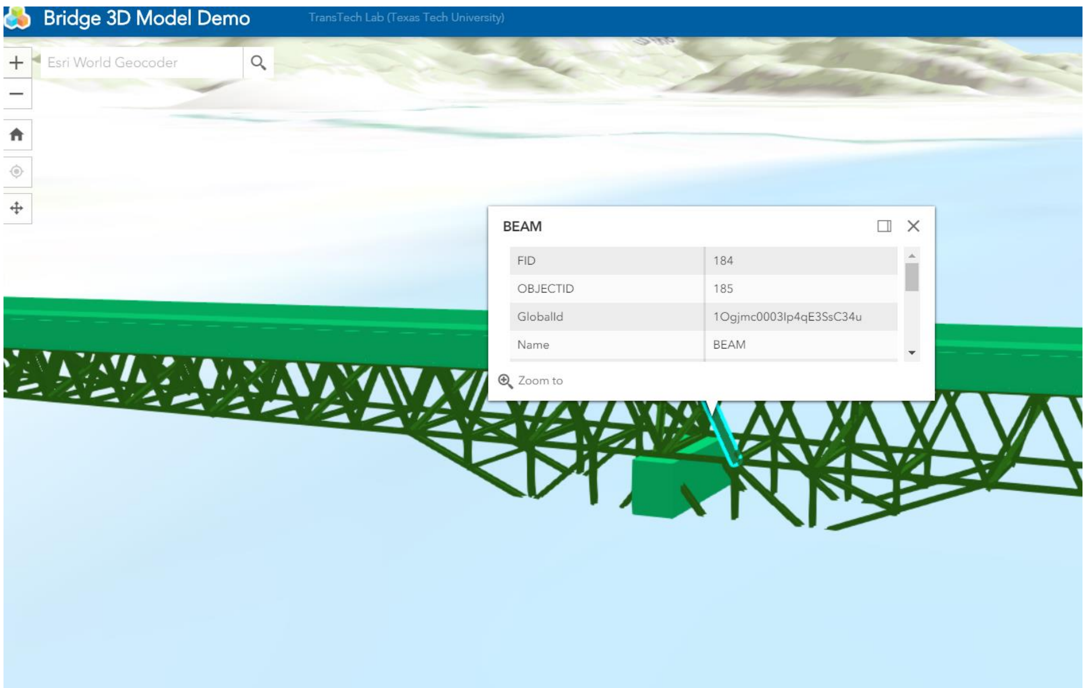

Figure 18 The bridge object information shown in the developed 3D BMS component

5. Conclusions

To address the limitations of existing BMSs, the researchers developed and implemented a web GIS-based bridge management system that allows for advanced geospatial visualization and potential data integration on a centralized cloud platform. The research team used Esri™ technology-based ArcGIS Online for the development of the proposed BMS. The developed BMS is designed as a bi-level platform, in which the upper level manages the overall bridge network based on two-dimensional (2D) vectors or images, while the lower level handles three-dimensional (3D) spatial information and real time data streams for monitoring the health of individual bridges. One major development of this project was an open source BMS prototype that can create custom applications, provide a platform for integrating GIS with other business systems, and enable cross-organizational collaboration. The prototype aims to provide an open-source architecture for the public. Its architecture and codes will be open to end users and thus can be easily customized by any transportation agency for their bridge management needs.

The specific tasks of this project were: 1) to provide a comprehensive review of current BMS development activities; 2) to identify available bridge-related data sources at the state DOT that enable the further data integration needed for a variety of analytical purposes; 3) to build a more realistic model to represent the deterioration of bridge components by using a semi-Markov transition process. The semi-Markovian transition probabilities will be derived directly by accessing and analyzing the NBI database; and 4) to develop a web GIS-based bridge management system that allows advanced geospatial visualization and potential data integration on a centralized cloud platform. The pertinent bridge maintenance data includes text, images, engineering documents, citizen reports, and remote sensing data.

The proposed BMS can be enhanced greatly by further development if additional time and funding are available:

- The proposed semi-Markov process-based bridge performance model can be designed as a widget and integrated into the tool. This should allow bridge managers to generate the life-cycle performance model for their bridges and optimize their management strategies based on it.

- By enhancing the 3D component, the bridge health monitoring information should be seamlessly transmitted to the 3D bridge model.

References

[1] Cardno, C., *Analysis reveals 58,495 US bridges are structurally deficient.* Civil Engineering, 2016.

[2] Herrmann, A.W. *Asce 2013 report card for america's infrastructure*. in *IABSE symposium report*. 2013. International Association for Bridge and Structural Engineering.

[3] Design, U.S.F.H.A.B.D. and I. Branch, *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges*. 1979: Department of Transportation, Federal Highway Administration.

[4] Ryan, T.W., et al., *Bridge inspector's reference manual.* Report No. FHWA NHI, 2006: p. 03-001.

[5] FHWA, *Recording and Coding Guide for the Structure Inventory and Appraisal of the National Bridges*. 1995, U.S. Dept. of Transportation: Washington, D.C.

[6] TxDOT. *Texas Bridge Inspection Manual*. 2013; Available from: http://onlinemanuals.txdot.gov/txdotmanuals/ins/ins.pdf.

[7] Hammad, A., et al., *Mobile model ‐ based bridge lifecycle management system.* Computer ‐ Aided Civil and Infrastructure Engineering, 2006. **21**(7): p. 530-547.

[8] Czepiel, E., *Bridge management systems literature review and search*. 1995.

[9] Ryall, M., *Bridge management*. 2007: CRC Press.

[10] IABMAS. *The IABMAS Bridge Management Committee overview of existing bridge management systems*. in *5th Int. Conf. on Bridge Maintenance, Safety and Management, Philadelphia*. 2012.

[11] IABMAS. *The IABMAS Bridge Management Committee overview of existing bridge management systems*. in *5th Int. Conf. on Bridge Maintenance, Safety and Management, Philadelphia*. 2014.

[12] Ng, S.-K. and F. Moses, *Bridge deterioration modeling using semi-Markov theory.* A. A. Balkema Uitgevers B. V, Structural Safety and Reliability., 1998. **1**: p. 113-120.

[13] Wu, D., et al., *A life-cycle optimization model using semi-markov process for highway bridge maintenance.* Applied Mathematical Modelling, 2017. **43**: p. 45-60.

[14] Liu, H., et al., *Web-based routing assistance tool to reduce pavement damage by overweight and oversize vehicles*. 2016, Texas Tech University. Center for Multidisciplinary Research in Transportation.

[15] Wu, D., et al., *The assessment of damage to Texas highways due to oversize and overweight loads considering climatic factors.* International Journal of Pavement Engineering, 2017: p. 1-13.

[16] Wu, D., et al., *Evaluating the Impact of Oversize and Overweight Loads on Highways in Different Climate Zones: Texas Case Study 2*. 2017.

[17] Wu, D., C. Yuan, and H. Liu, *A risk-based optimisation for pavement preventative maintenance with probabilistic LCCA: a Chinese case.* International Journal of Pavement Engineering, 2017. **18**(1): p. 11-25.

[18] Wu, D., C. Yuan, and D. Wei, *Risk-based life-cycle cost analysis in preventive pavement management: a chinese highway case*. 2014.