6 Next Generation of Transportation Infrastructure Management: Fusion of Intelligent Transportation Systems (ITS) and Bridge Information Modeling (BrIM)

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Abstract

Bridges are one of the most important elements of the sustainable transportation infrastructure network that require significant care and consideration. Aging and deterioration are two main complications in their operation and maintenance that require precise data and efficient technologies to improve the quality of their lifecycle management. Intelligent transportation systems (ITS) have been altering the infrastructure management process by converting it into an automated process to capture, store, analyze, and manage the data. While the data have helped the management process, the issues of heterogeneity of the data and non-interoperable databases are still challenges for fully integrated management of the infrastructure. Thus, there is a crucial need for an integrated database that can help in consolidation of data management. Building Information Modeling (BIM) is one of the recent technologies that its benefits have motivated its utilization in the transportation infrastructure, and their specific use for bridges is known as Bridge Information Modeling (BrIM). Currently bridges are being inspected biannually and only structural data are being recorded for their assessment. This paper suggests the inclusion of traffic data in lifecycle management of bridges and introduces ITS as a great source of data, and BrIM as a great visual database that can help in enhancing the integration and management of databases. Fusion of ITS data with BrIM can provide many benefits for efficient operation and management of bridges that eventually improves the quality of facility management and helps as a reliable tool for decision making and budget allocation. In this paper, BIM and ITS capabilities have been discussed and finally a framework has been suggested to illuminate the dataflow process.

Keywords

Intelligent transportation systems (ITS) • Bridge information modeling (BrIM) • Bridge inspection • Operation and maintenance • Data management

6.1 Introduction

Reliable, safe, and efficient ground transportation network is one of the most important pillars of every country. The key to superior operation and management of infrastructure, especially bridges, is having plenty of timely and reliable data accessible. Aging and deterioration are two main complications about bridges [1, 2]. Thus, they are needed to be inspected routinely and accurately to ensure the reliable flow of traffic stream over the network. Bridge inspections provide a comprehensive overview and data about the bridge health status that help in understating their need for repair or rehabilitation, which enables robust decision making about allocating the required budget and resources accordingly.

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However, the amount of manual inspection needed with the lack of funding is a major challenge [3]. The cost of data collection for evaluation of the transportation network is high, as it requires considerable amount of time and experienced technicians and inspectors. Inspections causes lane closures and traffic delays that can negatively affect the commuters and economic impact. Furthermore, inspectors and crews can be placed in unsafe situations that increase the risk for the whole process [4].

While the structural inspection information is beneficial for the maintenance and management of bridges, there are some deficiencies. From a structural aspect, McGuire et al. [5] stated that collected data is only reflecting the description of the fault and its position, but neither reflecting its effects on the load bearing capacity of the bridge, nor providing useful information for enhanced management of bridge operation. This presents a major need to ensure bridges are continually inspected to prevent disastrous failures or collapse. However, traditional bridge inspection methods are risky, difficult, and prone to error [6]. Inspections are conducted and based on the inspector's experience and expertise, and errors are likely to occur due to personal judgment [7]. Furthermore, rehabilitation takes a great amount of time, effort, and monetary investment [8]. Therefore, there is a great need for an efficient, cost effective, and reliable method for bridge inspection and management to ensure safe and reliable passage. Different technologies are now helping inspectors and state departments of transportation (DOT) to capture considerable amount of data with higher precision and degree of reliability. Shaghlil and Khalafallah [4] reviewed how new technologies can help in monitoring the condition of road, and analysis of the damage severity, and help in better determination of maintenance needs. For example, laser scanners mounted to truck and drones are now being used for monitoring road distress and defects, which have reduced the inspection costs, increased safety, and optimized the accuracy of the captured data.

While the structural and physical assessment of roads and bridges are vital for transportation network, this research hypothesizes that real-time traffic data can enhance the quality of assessment, judgement, and decision making. Supplement to structural data, traffic data could help in better assessment of the real status of dynamic stresses and strains and fatigues that are being imposed to the bridge, in which knowing the utilization of bridges can help with preventative maintenance. Miao and Chan [9] used Weigh in Motion (WIM) data for modeling live loads on a short span bridge and compared it with other common loading models that yielded satisfying results. Mahmoud Khan et al. [10] assessed the integration of Intelligent Transportation System (ITS) with Structural Health Monitoring (SHM) systems and concluded that their integration can improve the efficiency and reliability of bridge management system. Lan et al. [11] used SHM and traffic data to improve the predictive probabilistic models for estimation of fatigue damage on bridges that eventually helps in better management of bridge defections.

The inclusion of traffic could enhance the quality and accuracy of maintenance planning, which ultimately helps in optimization of resource and budget allocation for the preservation of bridges (e.g. high utilized bridges would get inspected more frequently than less utilized bridges). To test this hypothesis, this paper first presents Intelligent Transportation Systems (ITS) as a great source of traffic data and identifies Bridge Information Modeling (BrIM) to supply the structural and other bridge information. The integration and fusion of heterogeneous traffic and structural data in BrIM could potential assist in efficient and cost-effective decision making for bridge maintenance.

6.2 Methodology

One goal of this research is to identify different applications of ITS and BIM and develop a framework to promote the fusion of these technologies and support efficient and cost-effective bridge operation and maintenance. The research aims to find an efficient method for integration and centralization of ITS data, so the data could be effectively shared and used by different stakeholders. The paper contributes to the body of knowledge by providing a review of intelligent transportation systems (ITS) and Bridge Information Modeling (BrIM), including the various technologies, components, and data types. The review uses qualitative and quantitative methods for the assessment. Additionally, review provides a holistic view about the data, application, and extent of ITS. The paper also presents the novel framework of the ITS and BrIM integration. Potential applications, opportunities, and challenges of this integration are discussed. Although the current scope of this research is for bridges, results of this approach could potentially benefit and enhance the design, management, and maintenance process of other transportation infrastructure. The main objectives of this research can be categorized as follows:

1. Investigate the capabilities and applications of ITS as an automatic data collection system and the extent of information which could be achieved.
2. Determine proper automated data capture methods for better flow and storage of acquired data.

3. Design methods that can help in automation of database establishment and enrichment and increase the efficiency and comprehensiveness of collected data.
4. Evaluate the extents of the capabilities achieved by this approach and the potential benefits of the data produced for the stakeholders.

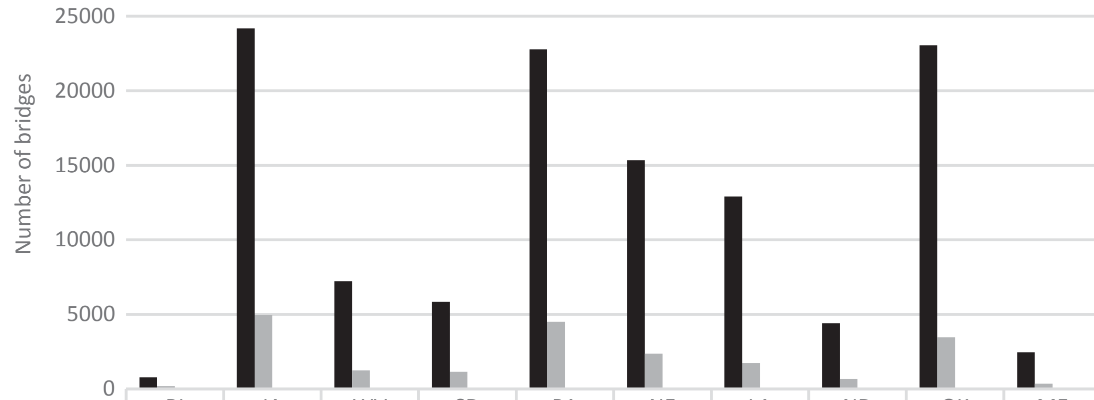
This research first conducted an exhaustive literature review about the use of BIM in the transportation infrastructure [12]. Using the same methods, this paper focuses on applications specifically relating to ITS. To obtain a comprehensive understanding about ITS and BrIM, a keyword-driven search was conducted in online databases with academic focus including Google Scholar, EBSCO and SCOPUS. The search has been conducted with the general keyword "Intelligent Transportation Systems" or "ITS" and has been narrowed down to the research that discuss various ITS systems and their application. The same process has been conducted using keywords "BIM," "Building Information Modeling," "Bridge Information Modeling," "bridge," "bridge inspection," "bridge maintenance," and "infrastructure maintenance." Then, each abstract and conclusion were reviewed to determine if the article contained the data about the ITS and their applications. Once it was determined that the paper was relevant to the review, it was fully reviewed and data was extracted and stored in an application and database. The reviewed papers contained information about (1) applications of technology, (2) benefits and potential research developments, (3) limitations and challenges. The reviewed articles consisted of 11 journal papers, 5 conference proceedings, and 2 reports. The reports that have been retrieved from Federal Highway Administration (FHWA) and State DOTs websites were used as the primary source for quantitative representation and analysis. ITS devices and systems have been introduced and the type of data that they can produce have been introduced. After gaining the understanding about ITS and BIM specifications, a framework has been proposed for their integration.

6.3 Overview of the Current Infrastructure

According to the recent ASCE infrastructure report, 9.1% of the more than 600,000 bridges across the United States are structurally deficient, while having an estimate of 188 million trips over them during 2016, showing the great concern of safety risks [13]. Currently, a considerable number of these bridges need maintenance and repair [14] and estimated cost for their rehabilitation and repair is roughly $123 billion [13]. Furthermore, the cost for the maintenance and repair of other civil infrastructure is even more staggering. Potholes, patching, cracking, and deformation of surface are the most common road surface defects. These problems damage the passing vehicles and impose costs to drivers and government [4]. From another perspective, the increase in the fleeting traffic may either meet or exceed the maximum design amount, which causes excessive deterioration that also leads to backups and delays that imposes great waste to national economy. This is crucial as Sweet [15] stated that the hourly value of travel delays is $16.01 for private vehicles and $105.67 for commercial vehicles, and it is evident that congestion exacerbates these costs. According to Texas Transportation Institute, traffic delays imposed a $160 billion loss to the U.S. economy in 2014 [16]. Thus, it is significant that the structure and fleeting traffic of bridges should be constantly monitored to minimize any failure that leads to congestion and its negative effects on the transportation infrastructure and national economy.

To establish an understanding about the current situation of states that have the most problem with deficient bridges, a sample of 10 states that have the highest ratio of deficient bridges to their total number of bridges have been selected using the data from ASCE Report Card [13]. Figure 6.1 visually compares this ratio and shows that an average of 17.5% of bridges in these states are deficient. Additionally, these ten states have spent a total $2.5 billion for their bridges during the year 2016 and may need increase the budget with the increasing need for operation and maintenance.

The states that have high ratio of defective bridges require considerable amount of budget for their maintenance. On the other hand, some states like Texas have very high number of bridges that are not considerably deficient, but they also require high amount of budget for keeping their bridges in standard condition. Therefore, deciding about the budget allocation in national scale is a complex and crucial problem for decision makers and government, that needs comprehensive data and efficient analytical approaches. Figure 6.2 compares these two group of states and shows that difference in geographical location of these states can add another condition to the problem and increases the complexity of robust decision making for budget allocation for their maintenance.



	RI	IA	WV	SD	PA	NE	LA	ND	OK	ME
Total Bridges	772	24184	7217	5849	22791	15334	12915	4400	23053	2450
Deficient Bridges	192	4968	1247	1147	4506	2361	1739	661	3460	352
Ratio of deficiency	24.90%	20.50%	17.30%	19.60%	19.80%	15.40%	13.50%	15.00%	15.00%	14.40%
Budget expenditure ($M)	93.87	633.04	154.88	17.85	974.54	61.77	203.73	15.30	341.10	3.16

Fig. 6.1 Comparison of ratio of deficient bridges to all bridges for states with highest ratio of bridge deficiency

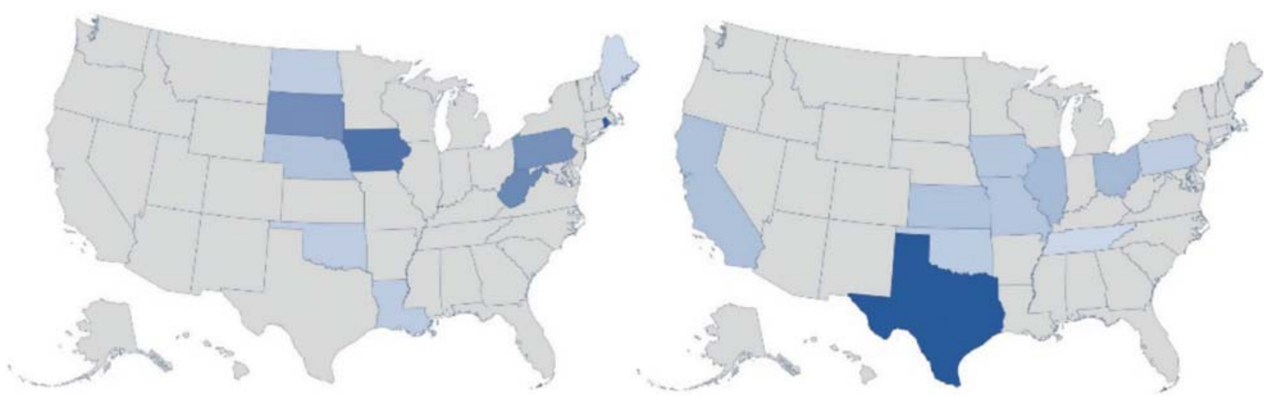


Fig. 6.2 Comparison of states with highest ratio of bridge defect (left) versus states with highest number of bridges (right)

6.4 Intelligent Transportation Systems (ITS)

ITS helps transportation infrastructure to be safer, more reliable, and more efficient [17], which is significant since the performance of transportation infrastructure has direct influence on economic growth of countries [18]. The following sections provide an overview about ITS and their extent.

6.4.1 Components of ITS

The focus of this paper is to identify the electronic devices and systems that capture and provide the real-time information to be used in BrIM. These devices could be generally categorized and discussed under mechanical sensor components and vision-based components. Other equipment including Variable Message Signs (VMS) and interactive interfaces are the devices that are being used for returning the results of processed data to the users for their information and direction.

Mechanical sensors are electronic devices that capture on-site traffic data. Mechanical sensors could be as simple as a closed loop sensor that count the number of passing vehicles, or as advanced as Weigh in Motion (WIM) stations that capture the complete properties of the commercial vehicles including speed, number of axles, weight, plate number, as well as their photo. Global Positioning System (GPS) is another good example of vehicle-based sensors that guide vehicles through their optimum routes while balancing the network congestion. With the development of sensing technologies, these sensors are now providing a considerable amount of real-time data which is known as Big Data [19].

Vision-based sensors use image processing technology to capture data. Cameras have been widely used for monitoring roads, automatic detection of congestion and accidents, speed enforcement, red light enforcement, and bus and high occupancy vehicle lane monitoring, etc. The captured data could later be used for statistical analysis and vehicle tracking and can also be analyzed through developing recognition models or rule-based reasoning logic [17]. These systems are easier and much cheaper to install, operate and maintain, and could be a proper replacement for human-operated tasks.

The result of captured and processed data needs to be relayed back to road users to update them with latest information about network. Different mobile applications are now using processed data to provide the live data for users. Variable Message Signs (VMS) are electronic signs installed across the highways and before the interchanges to inform drivers about driving conditions, such as emergencies, weather, and traffic conditions.

Table 6.1 shows a sample of data that could be captured by ITS devices and how different systems can provide various data to enhance the comprehensiveness. Significantly, amongst the suggested systems, Weigh in Motion Systems (WIM) are great components for capturing exhaustive information about fleeting traffic and their weight that could help in better assessment of bridges.

6.5 ITS-BrIM Fusion Data Framework

The current management of the captured data is a very intensive process, thus integrating the data with bridge information models (BrIM) could help inspectors and managers to have better control over the health of bridge. Database-enabled BrIM models could be a great platform for integration of these data as it can be connected to different databases and receive their information, while having the capability of storing and representing the summary of quantitative and qualitative data. The data could be retrieved and visualized through BrIM visual capabilities.

The ITS-BrIM fusion and data framework developed by this research is shown in Fig. 6.3. The data captured through different devices could be analyzed and used by different stakeholders, including structural designers, traffic engineers, transportation planners, operation and maintenance managers, project owners, state departments of transportations (DOTs), government authorities, and road users (e.g. commuters). The data can be captured through different ITS systems and stored in the database for analysis and record keeping. These data will be processed, and the pre-designed system will export different

Table 6.1 Sample of ITS captured data

Sensor type	System	Type of recorded data
Mechanical sensors	Weigh in motion (WIM)	Count Speed Weight Vehicle classification
	Inductive loops	Count Speed
	Electronic tolling	Count Charged amount
	Road Weather Information Systems (RWIS)	Wind speed Rain volume Humidity percentage
Video-based sensors	Video-based traffic count systems	Count Speed Traffic state Vehicle classification
	License plate readers	Vehicle plate information Origin-destination information

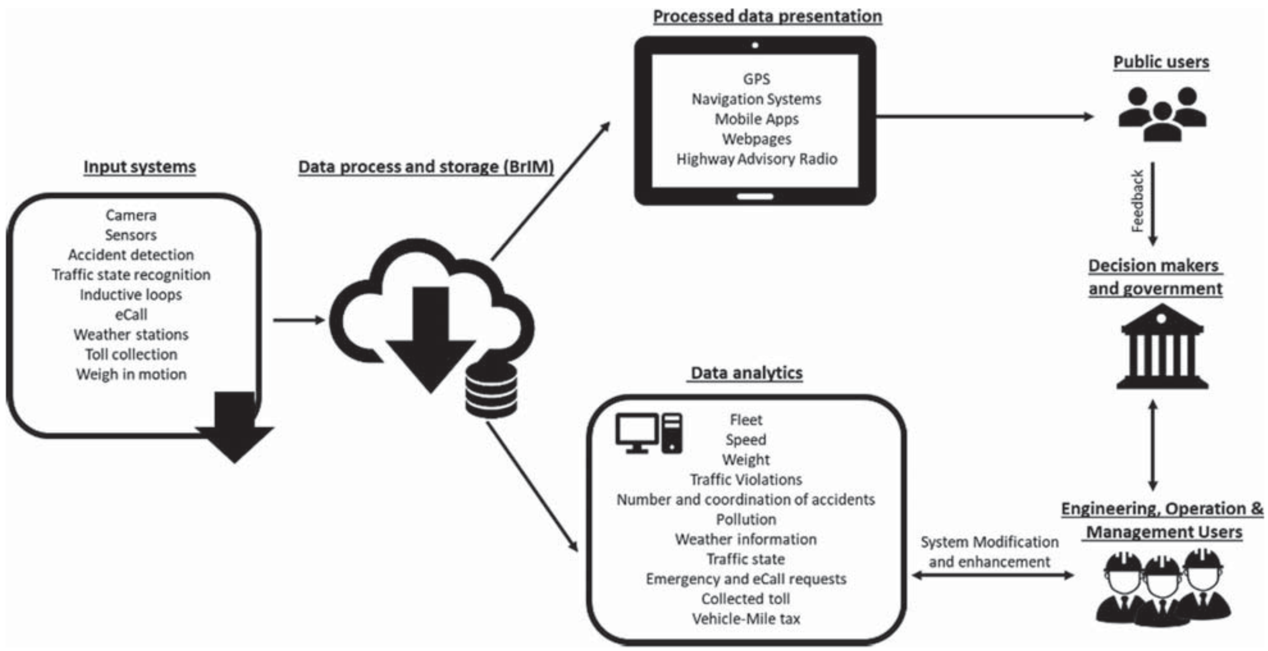


Fig. 6.3 ITS data framework

results. A portion of this result will be provided for public users (e.g. commuters) through interactive user interfaces including mobile apps or webpages. The system has real-time capabilities and will help users to fulfill their current need for real-time conditions about the road and infrastructure. This information may include the maximum allowable speed, height, and weight of the vehicle, as well as road congestion status, any possible accidents, tolling stations, etc. (refer to Table 6.1). Unlike the public users, the bulk of the data in the database will be available for the operation and management users, who are responsible for management, operation and maintenance of the infrastructure. State Departments of Transportation (DOTs) are examples of operation and management users.

The raw and processed data (e.g. speed, type and weight of passing vehicles, accidents, weather information, emergency requests, etc.) can be used for querying and data analytics. Managers, designers, and operators could use these data to evaluate the current traffic condition of the bridge and help the structural designers to have more parameters that may affect the bridge corrosion and deterioration and have better assessment and judgement over the structural health condition of the bridge. In higher administrative levels, this data could be evaluated and help in decision-makings about the best maintenance strategies for the bridge to maximize the efficiency and performance. As for any system, feedback is extremely important for system modification and data enhancement. This will help them in finding and modifying potential deficiencies and ensuring the operability of the infrastructure. This framework primarily shows the need for an integrated and centralized database, so all the stakeholders can benefit from the information. The individual BrIM models could later be developed on GIS-based platform to expand the BrIM capabilities into network scale.

6.6 Conclusion

Bridges are one of the critical components of road transportation network. Aging and deterioration affects commuter safety, while the fleeting traffic may exceed the design forecasts and exacerbate this deficiency. Real-time and reliable data can significantly enhance the bridge management, and ITS can automatically provide the required data. In this paper, different types of ITS and their obtainable data have been reviewed and a framework for better flow of data has been proposed. The review resulted in finding the following benefits:

– Current data that have been collected through different sensors could be associated and represented in a unified and visual database such as BrIM model that helps in their better understanding and utilization.
– The amount type of ITS equipment could be selected in accordance to the need and importance of the bridge.
– The ITS data utilization will be enhanced to satisfy the current expenditure on these devices and promotes future investments on these systems.
– The data could be visualized and presented through different media for operation and maintenance managers.
– Proposed system can provide data for the development of other research on bridges. Traffic analysis, structural analysis, sustainability analysis, maintenance cost analysis, and road deterioration analysis are a few examples of development of utilization of this approach for helping the transportation infrastructure.
– The maintenance and management strategies and budget allocations could be adjusted due to better understanding of the conditions that are harming the bridges.

Despite the benefits, the review found these challenges and gaps for implementation of this approach the require further research:

- Although the data produced by ITS are useful in their own right, their heterogeneity may be an obstacle in full implementation of the methodology.
- Independence, dispersion, and heterogeneity of the data make the integration of databases difficult that may require innovative approaches in database design.
- The amount of data that has been produced by ITS devices is large in volume and that require automated algorithms and methods for their analysis and assessment.
- The streaming data needs to be associated with the BrIM model through online platforms. Testing and finding a proper online platform with compatibility for its connection with different databases could be a challenge in this process.

Significantly, the fusion of ITS and BrIM can ultimately provide one method of reducing the funding gap needed to maintain the vast network of bridges. This research will continue to follow the further steps for implementation of the proposed methodology and associate the ITS data with BrIM model.

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