

An Interactive Visual Analytics System for Bridge Management

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Abstract

Bridges deteriorate over their life cycles and require continuous maintenance to ensure their structural integrity, and in turn, the safety of the public. Maintaining bridges is a multi-faceted operation that requires both domain knowledge and analytics techniques over large data sources. Although most existing bridge management systems (BMS) are very efficient at data storage, they are not as effective at providing analytical capabilities or as flexible at supporting different inspection technologies. In this paper, we present a visual analytics system that extends the capability of current BMSs. Based on a nation-wide survey and our interviews with bridge managers, we designed our system to be customizable so that it can provide interactive exploration, information correlation, and domain-oriented data analysis. When tested by bridge managers of the U.S. Department of Transportation, we validated that our system provides bridge managers with the necessary features for performing in-depth analysis of bridges from a variety of perspectives that are in accordance to their typical workflow.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Picture/Image Generation—Line and curve generation

1. Introduction

Bridges are an important component of the U.S. transportation system, and maintaining their structural integrity is crucial to the safety of millions of people. However, bridges deteriorate over the course of their designed life cycles. The steel corrodes, the concrete spalls, and the stone cracks. Without proper maintenance, these deteriorations may cause severe damages that might lead to potential catastrophes.

In theory, bridge engineers can predict the service life of bridges based on computing each bridge's deterioration rate and establish a suitable maintenance plan [DET06]. However, since the presumed service conditions of a bridge may change, the bridge's deterioration rate often varies from its theoretical expectations. In practice, it has been observed that deterioration rates of similar bridges can vary significantly due to their local weather environments, traffic patterns, etc. [DET06]. Therefore, to ensure the integrity of a bridge and to prevent severe deteriorations, it is very important to establish regular inspections and to provide necessary bridge maintenances [Bri93] [MRG*01].

Since 1968, the U.S. Department Of Transportation (USDOT) has committed to monitoring and maintaining all bridges across the states. Currently, bridge inspections are typically completed over a 2-year cycle. According to the federal inspection coding guidance [Wes04], these inspections focus on assessing bridges from both structural and external factors, including physical structure conditions, traffic volume and patterns, surrounding environments, etc. At the end of a typical bridge inspection, over one hundred data items are often recorded and stored in a bridge management system (BMS) [Hea07]. This collected data subsequently serves as input to most bridge managers' maintenance planning processes.

Given the importance of bridges, one would hope that most bridges are maintained in a timely manner. However, according to the 2009 American Society of Civil Engineers report, currently more than 26 percent of the nation's 599,766 bridges are either structurally deficient or functionally obsolete [Ame09]. Furthermore, given the limited budget and other resources, not all of the bridges can be main-

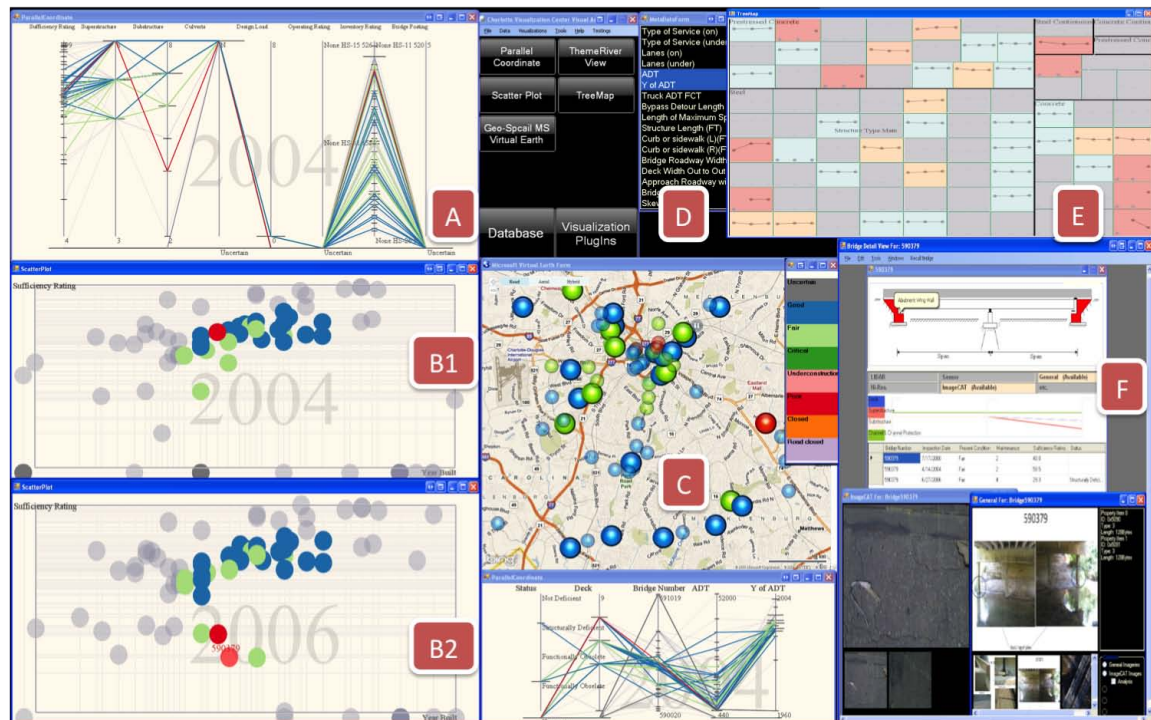


Figure 1: This is the overview of the entire system, including views for Microsoft Virtual Earth(center), Parallel Coordinates (top corners), Scatter Plots (middle left), Temporal Analysis (third row right), and the original data (bottom row). Per-Bridge Detail View(middle right). Several items are highlighted with colors.

tained immediately. In order to utilize the limited budget and resource effectively, most bridge managers develop their own strategies to prioritize and determine the order in which bridges should be maintained.

While these strategies have largely balanced the limited resources with the upkeep of bridges across the country, the collapse of the I-35 bridge in Minneapolis during August 2007 serves as a devastating reminder that the complexity of bridge management still demands novel techniques and proper tools to interpret and understand bridge data. Therefore, soon after the tragedy, members of our university formed a research partnership with the USDOT, the North Carolina State Department of Transportation (NCDOT), and the American Association of State Highway and Transportation Officials (AASHTO) to investigate novel approaches in assisting the bridge management process.

One of our first actions under this research partnership was to conduct a nation-wide survey [CRR09] to understand the usage of current BMSs and to identify potential areas of improvement. 35 out of 50 state DOTs responded to our survey, and the result indicates that the current bridge management systems are often insufficient in supporting bridge analysis. Almost all the responded states expressed the need

of having a management system that enables them to be more effective at analyzing their bridges, and the system needs to be customizable for assisting their individual workflows.

Based on their feedback, we identified three types of bridge analyses that are often essential in bridge manager's decision-making process, namely, structural analysis, temporal analysis and geospatial analysis. While the use of these three analysis processes and their usage patterns may vary in each bridge manager's workflow, we have found these analysis steps to be necessary for bridge managers to analyze the bridge data, understand the severity of deteriorations, and to make further maintenance decisions.

Using these three analysis processes as foundation, we designed and developed an interactive, exploratory visual analytics system for analyzing bridge data. Our system encodes the three processes as a group of four coordinated visualizations and allows the bridge manager to choose different combinations of visualizations and to customize them to fit into their own analysis workflow. To evaluate the system, we conducted expert evaluations with bridge managers from NCDOT and found that most managers believed our system to be useful and complimentary to their existing analysis

processes. We further identified ways in which our system could be quickly incorporated into their daily routines.

The remainder of this paper is structured as follows: Section 2 characterizes the analysis processes of domain experts and describes our system's targeted users. Section 3 provides more detail about the limitations of current BMSs. Section 4 presents our visual analytics system. Section 5 provides several scenarios in which our system can facilitate bridge management. In Section 6, we present our evaluation with domain experts and our discussion for advancing from current stage, and we conclude our paper in Section 7.

2. Domain Characterization

Bridge maintenance workflow is a process of deciding the severity, trending, relevance, and benefits of maintenance work on a specific bridge as well as a network of bridges. According to AASHTO's asset management guidelines [AAS03], the first step in this process is to gather relevant data about a particular bridge, including its known damages, previous maintenance histories, and typical deterioration patterns. Bridge managers will then start analyzing the obtained information, identifying the needs for maintenance and coming up with proper maintenance plans.

According to bridge managers from NCDOT, it is fairly common for a bridge manager to be responsible for hundreds of bridges. Since federal guideline dictates that bridges are inspected on a biennial basis, approximately 50% of the bridges are inspected in a given year. However, in that same year, only a portion of the bridges, approximately 20% - 25%, would require any maintenance attention. Even fewer bridges (around 10%) may actually receive maintenance work. Given the complexity of these inspection results, compounded with external constraints on budget and resources, a bridge manager needs to have complete understanding of all bridges under his/her jurisdiction when making maintenance decisions.

It is therefore necessary to have a BMS that monitors and analyzes the conditions of bridges in a way that allows a bridge manager to maintain an overview of all bridges and yet retain the capability to inspect detailed information of a particular bridge. Currently, there are a few available BMSs such as Pontis [WR03] and BRIDGIT [HS98] that promise analytical capabilities. However, there exist many limitations and issues with these BMSs (some of which will be described in detail in the following section), many bridge managers, including a few from NCDOT, still rely on using simple spreadsheets such as Microsoft Excel to perform their analyses.

3. Identifying the Limits in Current BMSs

Together with USDOT, we conducted a nation-wide survey to analyze the current usage of BMSs [CRR09]. Our survey focused on collecting information about the utilization

of BMS in each state, and asked for feedback on the utilities of those systems. As listed in the following table, our survey was centered around these three substantive questions:

1	What do you see as the most important next step in the further development of your agency's BMS ?
2	What do you see as the necessity of expanding current BMSs?
3	What are the biggest barriers in your department in implementing innovations that may strengthen your BMS?

Table 1: The three substantive questions for all the state DOTs in the U.S.

Of the 50 state DOTs that we contacted, 35 of them responded. For each state, we contacted multiple bridge managers and collected questionnaires from them individually. We received a total of 71 questionnaires from these states. The result of the survey indicates that while the BMSs used at these state DOTs are very efficient at data storage, they are not as effective in providing data exploration or domain-specific data analysis. Based on the response of these state DOTs, we categorize the limitations of existing BMSs into three major areas:

- **BMSs have not provided effective support for bridge managers' decision-making processes.** Many states have reported that they mainly utilize BMSs as data storage software. Although some BMSs have certain automatic decision making support capability [WR03], their analysis tools are not appropriate or adequate to be incorporated in to a bridge manager's analysis process.
- **BMSs are rigid in structure and cannot be easily adapted to support individual bridge manager's task routines.** Many states have reported that it is difficult for them to customize BMSs to suite their own analytical approaches. These states have also indicated that it is very difficult for them to implement additional features within these BMSs.
- **BMSs have not provided abilities to incorporate local inspection technologies.** Many states have their own inspections results that are complementary to the national standard inspections. However, as reported by state DOTs, it is often difficult to import such information into the data structure that these BMSs provide.

In summary, almost all state DOTs have expressed the need of having a BMS that enables them to be more effective at analyzing their bridges. Additionally, they have helped us identify their domain problems and encouraged us to design a system that can assist their decision-making processes.

4. Characterizing the Domain Problems

As indicated by the result of the survey, there are three challenges in existing BMSs: the insufficient support for analytical processes, the restrictions in personalizing analysis routines, and the difficulties in integrating heterogenous data.

Therefore, the primary goal of our system is to address these challenges in accordance to the needs of the bridge managers at these state DOTs. The detailed characterization of these three challenges, as well as how they are addressed in our system are described in the following sections.

4.1. Providing effective support for bridge manager's decision-making processes

As the state DOTs noted, current BMSs are effective at storing data, but are insufficient at supporting analysis processes. In order to address this shortcoming and to provide support for bridge analysis, we worked with bridge managers at NC-DOT to identify three analyses that are often essential to their decision-making process: structural analysis, temporal analysis, and geospatial analysis. According to these bridge managers, these analyses help them analyze bridge data from different perspectives and are integral to their daily workflows.

- **Dynamic Geospatial Analysis:** Bridges exist in a dynamic environment with changing surroundings. Therefore, rather than using a static map, bridge managers often need to adapt to new situations and analyze bridges with additional information such as traffic patterns, flooding regions, and population densities. According to bridge managers, supporting dynamic geo-exploration is a primary area for bridge analysis.
- **High Dimensional Structural Analysis:** Typically, the data representing bridge structures are high in dimensionality. Federal regulation requires bridge inspection to record nearly 130 structural variables biennially. Given the complexity of the data, a tool that could assist bridge managers' comprehension of these variables would be essential. Specifically, on a high level, bridge managers need to detect and identify causal relationships and trends in these variables so that they could identify phenomena that are affecting all bridges. On a detailed level when inspecting a single bridge, bridge managers need to examine the overall structure integrity of a bridge across multiple variables and to focus on particular structural components inside that bridge.
- **Scalable Temporal Analysis:** Through analyzing the temporal changes of a bridge's condition, bridge managers can compute the deterioration rate of the bridge. In addition, bridge managers can adjust the future maintenance plans by assessing the outcomes from previous work. Therefore, the ability to capture the temporal information is of great value to bridge managers when planning for future maintenances. However, temporal analysis in most existing BMSs is limited to analysis on a per bridge basis. Having an overview that could help the bridge managers spot bridges with abnormal temporal behaviors would be very beneficial.

4.2. Supporting Individual Manager's Task Routine

Our survey also suggested that current BMS are quite rigid in supporting individual bridge manager's task routines. As noted in Section 2 bridge managers often need to develop their own analysis routines. Depending on available resources, a bridge manager's strategy can be very different from his/her peers', and would require a different combination of the above analysis processes. In addition, sometimes even the same manager needs to take alternative analytical approaches due to changes in priorities. At the heart of these individual routines are the different combinations and sequences of the above analytical processes. Therefore, it is rather important for a system to provide bridge managers with the flexibility to combine and sequence these analytical processes to fit their own workflows.

4.3. Supporting Integration of Local Inspection Technologies

While this is an important issue for the bridge managers, solving it begins with designing new data structures for the BMS. Currently, given the rigid nature of existing BMSs, supporting data integration would require an overhaul of the designs of these BMSs. We have begun discussions with AASHTO to improve the capabilities of BMSs in providing such integrations, but it is outside of the scope of this project.

5. The Visual Analytics System

Based on the requests of state DOTs as described above, we design an interactive visual analytics system (Figure 1) that supports a bridge manager's decision-making process and remains customizable to fit an individual manager's task routine. The design of our system is based on coordinated multiple views (CMV) [Rob07], as well as a modular software architecture that supports customization of the system depending on the bridge manager's preference.

5.1. Supporting Decision-Making Process through Multiple Coordinated Visualization

In order to provide bridge managers with analytical capability, our system encodes the three analyses processes described in the previous section into a set of coordinated visualizations. In the following sections, we describe how each process is depicted in our system.

5.1.1. High Dimensional Structural Analysis

Our system includes three views for helping bridge managers to analyze bridge structures on both a high-level overview and a low-level detail view. On the high level, our system utilizes both a parallel coordinate view (PCView, see Figure 1 (A)) [Mol05] and a scatter plot view (SPView see Figure 1 (B)) [Tuf90] to help bridge managers detect and

identify causal relationships and trends in the data variables. The nature of parallel coordinates limits the number of dimensions that can be effectively displayed at a time. Our implementation therefore provides control panels to allow the user to select the dimensions of interest (Figure 1 (D)). These dimensions are determined by individual expertise and bridge managers' areas of focus. For example, a structural engineer is more likely to examine bridges based on the structural related dimensions, whereas a planner would focus on analyzing dimensions that represent balances between costs and potential bridge improvements. Using this view, bridge managers can therefore find correlations in specific sets of the bridge's attributes.

On the other hand, the SP view is designed to depict relationships between bridges across two specific dimensions. The spatial layout of the view allows the user to see clusters and clearly identify outliers, and is a slightly more intuitive interface than the potentially complex PC view. In addition, given the importance of time in bridge analysis, our system also extends the ability to see temporal changes in both views, which in turn allows bridge managers to interactively explore and compare information from different inspection cycle. For example, Figure 1 (B1) suggests the sufficiency rating distribution in year 2004, while Figure 1 (B2) shows the distribution of same group of bridges in year 2006. Together, these two visualizations give bridge managers the ability to see high-level trends and patterns in the data's variables.

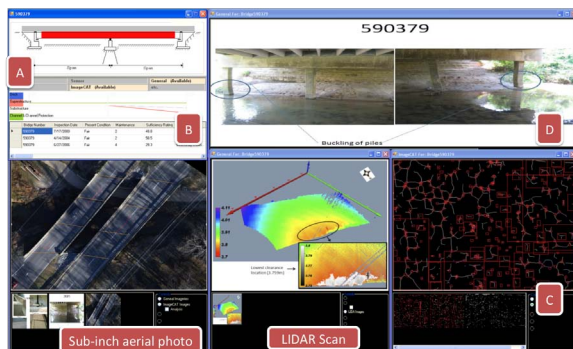


Figure 2: The Detail View for Bridge (A) An interactive Bridge Schematic Diagram; (B) A Line graph for monitoring temporal changes for major bridge structures; (C) Image Analysis Results for cracks on pavements; (D) Inspection Imageries that suggests the structural damage of the supporting piles of this bridge.

On a detailed level, when inspecting a single bridge, bridge managers need to examine both the overall structural integrity of a bridge across multiple variables, as well as focusing on particular structural components inside that bridge. Therefore, we design a structural detail view to automatically link information between each bridge component

and provide bridge managers with an intuitive visualization to interactively analyze the corresponding structural information.

Based on existing bridge design guidelines [DET06], we model general bridge components into an interactive bridge schematic diagram (see Figure 2 (A)). In this diagram, bridge managers can directly select the major bridge structures, and analyze each component individually. In addition, a line graph enables bridge managers to monitor temporal changes for individual bridge structures. Associated with overall temporal information presented in the small multiples view, this structural temporal component helps bridge managers to gain insight into the effects of structural changes, and to efficiently identify the key factors in the overall deteriorations.

5.1.2. Small Multiples for Temporal Analysis

Bridge managers have expressed the need of having a tool to help them analyze the temporal changes of bridge data. They want to be able to perform analysis over time on a large number of bridges as well as one bridge at a time. Thus, we design a small multiples view [Tuf90] to help them achieve temporal analysis of large number of bridges. Our design is based on small multiples views in the literature [KER09], and it shows deterioration changes of each bridge using trend lines.

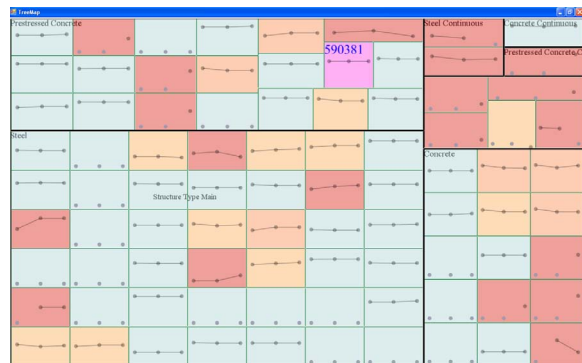


Figure 3: The Small Multiples view with Squarified Treemap layout. Bridges are grouped by their main structure types. For each cell, the x axis represents different inspection cycles and the y axis represents the structural attribute values selected by the user.

As shown in Figure 3, each cell in this view represents a single bridge, while the inside line graph represents the bridge's overall rating in all inspection cycles. These cells are further sorted based on the standard deviations of the y axes in the line graph to determine the color of the cells, with warmer color representing sharper changes over time. We note that in this approach, bridges with either downward and upward trending in structural attributes will be colored

with warmer colors. Although it is not often that bridge managers need to review more than three inspection cycles (6 years), our small multiple views can still efficiently represent all the inspection cycles by changing the line graph to a trail enabled bubble chart, which is similar with the work by Robertson et al [RFF*08]. We also provide bridge inspectors a control panel to modify the mathematical functions used in highlighting the cells.

Additionally, since it is often necessary for bridge managers to understand the temporal patterns for a certain group of bridges, we applied a customizable Treemap [BHW00] spatial layout to group the small multiples based on particular structures. There were two main design considerations on utilizing this layout. On one hand, we consider Treemap layout for its inherent advantage in displaying large scale of data, as demonstrated by Bederson et al. [BSW02]. Since bridge managers normally need to monitor hundreds of bridges together, this scalability is useful for them to effectively compare difference bridges and see overall trends.

On the other hand, we utilize the Treemap layout to indicate the size and groupings of different bridges. For example, Figure 3 shows the bridges divided based on their construction material (note the black lines separating regions of the treemap). In this example, the layout enables bridge managers to discover the uncommon temporal pattern where several recently built, known-to-last, concrete structure bridges show significant deterioration. It is therefore mentioned by bridge managers that the capability in finding such insight is not only valuable for their maintenance decisions, but also can help optimize their future construction planning.

While there is still much to be improved for the small multiple view, bridge managers have already seen usefulness in utilizing it to analyze temporal trends and patterns among the bridges.

5.1.3. Geospatial Analysis

Extensive research on geospatial visualization [WDSC07, Fis07] have shown the benefits of utilizing online map systems such as Google Maps and Microsoft Virtual Earth. We utilize Microsoft Virtual Earth (MSVE [Mic09]) to provide bridge managers with dynamic and interactive geospatial analysis (see Figure 1 (C)). By placing the bridges onto the scalable map, detailed geographic relationships and patterns immediately become apparent.

By adopting online map systems such as MSVE, our system can have the most up-to-date geospatial information such as road structures and 3D building models. However, we further extended MSVE in our system to overlay large amounts of (proprietary) geo-coordinated information over the map, such as traffic distribution patterns and satellite images, and can utilize that information to perform extensive geospatial analysis.

5.2. Supporting Customization of the System

To adapt to the development of emerging domain technologies, our system is built on top of a modular architecture that allows bridge managers to extend the system to incorporate advanced visualizations and more effective data models. This is made possible largely because inspections and analysis results are tightly associated using a unique bridge identification number.

Therefore, each visualization component integrated in our current system is designed to be interchangeable with other equivalent visualizations if they both use the bridge identification numbers. Using our architecture, if bridge managers suggest new suitable visualizations for their analysis, our system would be ready to incorporate those visualizations to provide additional functionalities.

Furthermore, this approach enables bridge managers to combine the traditional National Bridge Inspection Standards (NBIS) dataset with their locally collected information. As of the paper, we have helped NCDOT bridge managers to associate bridge structural information with extensive data collected in the North Carolina region. This extensive information includes, as shown in Figure 1 (F), field inspections imageries, Light Detection And Ranging (LIDAR) scans for each structure, and pavement crack analysis results.

6. Example Scenario

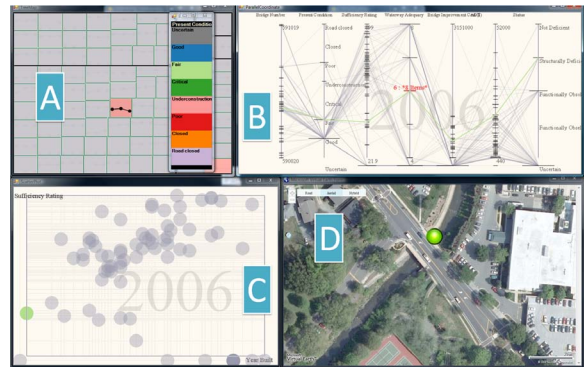


Figure 4: (A) A significant downward temporal trending indicates an unusual pattern (B) Using PCView to compare different structural attributes (C) Examining a certain bridge on SPView, indicating this is the earliest constructed bridge in the database (D) The Geospatial view shows that this bridge is constructed on top of a river stream.

Identifying and understanding the cause of bridge deterioration is a key step for bridge managers to come up with corresponding maintenance strategies. Based on our discussions with 9 bridge managers and bridge experts, it has been observed that there are generally three stages in achieving this step, namely, selecting bridge candidates, detailed examination, and identifying potential causes for damage. The

following scenario was identified together with 5 bridge engineers (4 males and 1 female) from Charlotte DOT's bridge management team for their annual bridge maintenance planning. During this process, these engineers were encouraged to collaboratively discuss the issues in a think aloud manner. As observers, we documented their process and help them to familiarize with the system. We also provided explanations about certain features in our system along their discovery.

Our system was initialized with data from previous three inspection cycles: years 2000, 2004, and 2006. The bridge management team started the maintenance process by searching for bridges with significant changes in sufficiency rating in the previous years. They utilized the small multiples view to see if any interesting bridge changing patterns could be identified. As shown in Figure 1 (E), the team found a set of bridges with warmer colors in the small multiples view, and they also identified several bridges with significant downward trends in the past years. By highlighting these bridges in the scatter plot view (see Figure 4 (C)), the team noticed that one of them was actually the oldest bridge in the Charlotte area. Suggested by both the small multiple view and the scatter plot view, this bridge actually shared the lowest overall rating in that year and had had drastic deteriorations since 2004.

To have a closer look at the bridge, the team used our geospatial view and zoomed into the bridge to check its surrounding environments. As shown in Figure 4 (D), this bridge was constructed over a river stream, and had supported high traffic volume because it had been chosen as a part of a detour route for a major interstate highway. These findings immediately raised several questions: could the bridge's deterioration be caused by water erosion, overloaded traffic, or flood damage? Although these were all possible causes of the deterioration, bridge managers had no definitive answers to confirm these hypotheses by looking at the geospatial view alone.

Trying to verify their hypotheses, the management team started to find clues from the structural reports of that bridge. By plotting the corresponding criteria in the parallel coordinate view, they found that the traffic amount on that bridge had not changed significantly in the previous years, and therefore ruled out the possibility of traffic pattern being the cause of the deterioration. However, the PC view showed that the water adequacy rating had dropped significantly during the past two inspections, suggesting the bridge had undergone severe water damage. To extract more detail, the team brought up the bridge's detailed structural view. As shown in Figure 2 (D), the supporting pillar for this bridge had shown heavy warping, and the bridge showed clear marks of water erosion near the bottom of the pillar. A quick reference check on the county's flood history confirmed that three significant flooding took place in years 2003, 2005, and 2006 around that area, which gave the bridge managers significant reasons to conclude that water damage, especially

flooding, was a key factor in causing the deterioration of this bridge.

Given the poor condition of its supporting structure, the bridge managers concluded that this bridge definitely needed maintenance attention. After the exercise, the management team commended the effectiveness of our system in assisting the identification of the deficient bridge, as well as the cause of the deterioration. Although simple, this scenario demonstrates a successful application of our tool in a real-world analysis application.

7. Expert Evaluation

In this section, we report the feedback from evaluations conducted with bridge managers at both NCDOT and City of Charlotte DOT (CDOT). A total number of 12 bridge managers (10 males and 2 females) participated in the three sessions of the onsite evaluations. Each of the sessions lasted about two hours.

First, we conducted a training session (30 - 40 minutes). During this session, we demonstrated the design of the system and the utilities of each visualization. Then, we invited bridge managers to perform in-depth analyses using the system (45 - 60 minutes). We encouraged them to carry out these analyses in a think aloud manner. We observed and documented the details about their analysis processes. Finally, we concluded the evaluation by a set of semi-structured questionnaires, which includes bridge managers feedbacks and comments about our system. Since bridge managers may need time to familiarize themselves with the all features provided by our visual analytics system, we also conducted email followups to see if there were additional comments they would like to share with us.

As of the current paper, we have kept communications with bridge managers about their comments of the system in the past 4 months and have gain significant insights for the continuation of this project. Although the degree and depth of analyses differed in each evaluation, the bridge managers generally agreed that our system provided more analytical capability than any existing BMSs, and that it is flexible enough for them to quickly incorporate the use of our system into their daily routine.

7.1. Visual Facilitation of Decision-making Processes

One benefit of our system that was noted by all bridge managers was that it provided a visual exploration environment to help them analyze information from multiple aspects. The capability of being able to perform not only geo-temporal analysis, but also structural analysis was of great value to bridge managers' decision-making process. One of the managers commented that, "[the] linked visualizations provide me with a cohesive understanding about the data that I am

working on. It reduces the time I spent on manually searching for information, and helps me focus more on the task itself.”

As demonstrated in the scenario (see Section 6), our system helped bridge managers to effectively analyze their data across multiple dimensions and assist them in determining the cause of deterioration. All the bridge managers found the system practical, and believed that the system would be valuable in their daily routines. One of the managers from NCDOT noted that, “...using your system, I can see correlations that I normally wouldn’t be able to see. This is much easier than making the similar observation from using our current system.”

In particular, 7 out of the 12 bridges managers pointed out that the temporal analysis in our system provided them with the capability to effectively monitor changes in bridge conditions and identify maintenance candidates. Specifically, an bridge manager from NCDOT commented on the temporal view that, “[one] can quickly scan with the eyes to have a sense of [the structural value changes of] a chunk of bridge”. He further saw the value of applying this technique to volumes of bridges. “Again, if you get volumes of bridges, this is a pretty nice feature to have.”; and he implied that this view made it more straightforward to locate and select individual bridges with different temporal trends.

In addition, after familiarizing themselves with the concepts and usage of the PC View and SC View, most bridge managers (9 out of 12) noted that the capability to examine bridge structures from multiple levels (overview and detailed view) could effectively guide them from examining large amounts of data to inspecting bridges one at a time. One of the bridge structural engineer commented on these views that, ‘visually grasp numerical value on a more timely manner and more manageably done, makes it easier to cross reference multiple bridge [structural] variables back and forth’. Although three of the experts did not immediately see the benefits of using the PC View, they later reported that, “with more time to play with your system, it appears to me that these views can be helpful to examine different bridges and understand their structural patterns”.

In summary, one bridge manager from USDOT commented that, “...using your system, we can now see what we normally can’t see. We also could have a cohesive understanding about our bridge assets. This would be helpful for us to identify and prioritize bridges...”. This confirms the utilities of our system.

7.2. The Flexibility to Assist Individual Workflow

At the heart of our system is a modular software architecture. This design provides bridge managers with the flexibility to customize system, and allows them to only utilize the necessary visualizations in their practices. As pointed out by a manager from CDOT, “[your system] will greatly shorten

the catch-up time between my learning to use the system and my actual use of it.”

Additionally, this modular design also allows our system to keep up with the development of the bridge inspection technologies. We are currently working with NCDOT to integrate their extensive inspection data into the system and customize the system for their needs. According to a bridge manager from USDOT, “true to the goal of the project, this system allows us to think about how we could have more practical impacts with integration of other technologies. As such, it gives us an opportunity to deploy the system to other state DOTs”.

8. Discussion

In this section, we discuss the current limitations of our system and future research directions.

8.1. Visualizations to Facilitate the Prioritization Process

While data analysis using our system can assist bridge managers in identifying candidate bridges that are structurally deficient, finding these bridges is just the first step in achieving overall maintenance decisions. There is an important prioritization process to decide which bridge actually receives maintenance that takes place after the candidates have been identified. As noted in section 2, this prioritization process is necessary due to limited resources such as budget and construction timings. Due to such constraints, bridge managers often need to find a balance between limited resources and maintenance requirements to maximize the overall stability of the transportation system as well as the safety of the public.

Unfortunately, such an optimization process is often not well defined, and the maintenance decisions vary depending on the goal of individual bridge managers. For example, some managers may focus on repairing supporting structures of bridges, which they believe is crucial to the bridges’ structural integrity, while others may spend the resources on fixing the bridge deck where visible damages occur. Although there are always uncertainties and variations in this process, it is clear that bridge managers need to have adequate strategies and tools to help them find the most optimal solution.

Our current system mainly focuses on providing data analysis, but not prioritization. According to bridge managers, it would be quite useful to extend our system’s ability to support both stages and help them optimize maintenance decisions. We have started discussing the possibility of extending our system with bridge managers, and the design of a constraint-based interactive visual analytics system would be one interesting future direction of our project.

8.2. Externalize the bridge manager's domain knowledge

Analysis of high-dimensional bridge data is generally performed by bridge managers who have a great deal of experience and special training, both of which are valuable domain knowledge. It is therefore interesting to consider whether externalizing such domain knowledge and reapplying it into customized visualizations would be feasible for enhancing bridge maintenance decisions. Although there is no definitive way to achieve complete knowledge transfer, existing research that has demonstrated how to incorporate visualization with domain specific knowledge [XGH06, GNRM08]. To achieve similar knowledge externalization, we propose a tight integration of the visualization with an ontological knowledge structure that could interactively capture and store the user's interactions and translate them into domain knowledge [WJD*09]. This externalization could further be used in training new managers, communicating with others, and reporting decisions.

8.3. Combine Decision-making Model with Visual Analytics System

Although our system has been very well received by DOTs of all levels, there has been some discussions in using automated analysis tool versus explorative visual analytical tool. In bridge management, existing BMSs, such as Pontis [RMSA02], include automated method like Markov models to predict the rate of bridge deterioration. While most bridge managers have rejected such methods because of concerns with accuracy, some bridge managers have also raised the question of how repeatable and reliable interactive visual analytics system can be given the subjective nature of open explorations.

We acknowledge that the support of explorations in visual analytical systems is an important challenge for the entire visualization community. However, in the context of bridge management, we propose that the solution is likely an integration of interactive techniques with automated ones. The challenge of such integration is the roles and relationships between the two components. At this point we do not have a clear outline on how to accomplish such integration that would leverage the strengths of both methods, but this is an important challenge that we will look to address in the near future.

9. Related Work

US and state DOTs have had a long history of adopting visualizations. As summarized in a recent survey by R.G. Hughes [Hug08], transportation visualizations can be generally categorized into two groups: (1) 3D visualizations that support design simulation and planning and (2) geographic information visualization that helps with data analysis and managing.

There is an extensive literature devoted to the use of visualization to support transportation simulation and planning. For example, both VISSIM [Vis08] and CORSIM [Uni06] are widely used to visualize traffic simulations and microscopic traffic controls. Also, 3D visualizations have been adopted to depict transportation designs and maintenance processes, such as NC3D [New09], a 3D visualization tool for designing high-speed railroads.

The field of geospatial visualization is a well-established area of research, especially in the field of Geographical Information Systems (GIS). Commercial GISs have also been developed to specifically help depict transportation data, such as GeoTrAMS [Int05], which is designed to manage train and rail assets, and TransCAD [Cap09], which focuses on road management. In visualization community, there are also extensive research on geospatial analysis. In addition to the systems we have referenced in Section 5, examples for geospatial research also include GeoVista by Takatsuka et al. [TG02] and GeoTime by Kapler et al. [KW04].

On the other hand, the use of visualization to perform bridge data analysis and bridge management is still in a preliminary stage. Although some simulation-based highway management systems have been developed [PTSR98], the main focus in this line of research is on depicting and extending knowledge of the geospatial nature in transportation information. Another notable analytical tool that partially includes bridge analysis is the work by Wongsuphssawat et al. [WPF*09] which performs data analysis of federal highway incidents. While both of these systems concentrate on analyzing transportation information, our system focuses on the interactive exploration and analysis of the relationships within the bridge data.

10. Conclusion

Maintaining bridges is a multi-faceted operation that requires both domain knowledge and analytics techniques over large data sources. Although current bridge management systems are very efficient at data storage, they are not as effective at providing analytical capabilities. In this paper, we present our interactive visual analytics system that extends the capabilities of current BMSs. As shown in Figure 1, our system was designed in collaboration with bridge managers in national, state, and local DOTs, and has been implemented specifically to provide them with interactive data exploration, cohesive information correlation and domain-oriented data analyses. Our system enables bridge managers to customize the visualization and data model to fit each individual's task routines. In our expert evaluations, bridge managers expressed their interest in using our analysis system and confirmed its novelty and utility over existing BMSs. With such encouraging feedbacks from domain experts, we are planning to deploy our system to multiple state DOTs and put our system in to real-world environments.

References

- [AAS03] AASHTO: *Transportation Asset Management Guide*. Tech. rep., NCHRP Project 20-24, January 2003. 3
- [Ame09] AMERICAN SOCIETY OF CIVIL ENGINEERS: 2009 report card for america's infrastructure on bridges, 2009. 1
- [BHW00] BRULS M., HUIZING K., WIJK J. J. V.: Squarified treemaps. In *In Proceedings of the Joint Eurographics and IEEE TCVG Symposium on Visualization* (2000), Eindhoven University of Technology, Press, pp. 33–42. 6
- [Bri93] BRINCKERHOFF PARSONS; SILANO L. G. (Ed.): *Bridge inspection and rehabilitation: a practical guide*. John Wiley and Sons, 1993. 1
- [BSW02] BEDERSON B. B., SHNEIDERMAN B., WATTENBERG M.: Ordered and quantum treemaps: Making effective use of 2d space to display hierarchies. *ACM Trans. Graph.* 21, 4 (2002), 833–854. 6
- [Cap09] CAPLIPER CORPORATION: *TransCAD, a transportation planning software*. Tech. rep., Capliper Corporation, 2009. 9
- [CRR09] COREY RICE XIAOYU WANG R. C., RIBARSKY W.: *A survey about the current usage of PONTIS across the U.S.* Tech. rep., University of North Carolina at Charlotte, 2009. 2, 3
- [DET06] DEMETRIOS E. TONIAS J. J. Z.: *Bridge engineering*. McGraw Hill, 2006. 1, 5
- [Fis07] FISHER D.: Hotmap: Looking at geographic attention. *Visualization and Computer Graphics, IEEE Transactions on* 13, 6 (Nov.-Dec. 2007), 1184–1191. 6
- [GNRM08] GARG S., NAM J., RAMAKRISHNAN I., MUELLER K.: Model-driven visual analytics. In *Visual Analytics Science and Technology, 2008. VAST '08. IEEE Symposium on* (Oct. 2008), pp. 19–26. 9
- [Hea07] HEARN G.: *Bridge Inspection Practices*. Tech. rep., University of Colorado, Boulder, 2007. 1
- [HS98] HAWK H., SMALL E. P.: The bridgit bridge management system. *Structural Engineering International Volume 8* (1998), 309–314. 3
- [Hug08] HUGHES R. G.: Research agenda for visualization in transportation. In *SIGGRAPH '08: ACM SIGGRAPH 2008 classes* (New York, NY, USA, 2008), ACM, pp. 1–5. 9
- [Int05] INTERGRAPH CORPORATION: *Geographisches Transport Anlagen Management System*. Tech. rep., Intergraph Corporation, 2005. 9
- [KERC09] KEEFE D., EWERT M., RIBARSKY W., CHANG R.: Interactive coordinated multiple-view visualization of biomechanical motion data. *IEEE Transactions on Visualization and Computer Graphics* 15, 6 (2009), 1383–1390. 5
- [KW04] KAPLER T., WRIGHT W.: Geotime information visualization. In *INFOVIS '04: Proceedings of the IEEE Symposium on Information Visualization* (Washington, DC, USA, 2004), IEEE Computer Society, pp. 25–32. 9
- [Mic09] MICROSOFT CORPORATION: *Microsoft Virtual Earth*. Tech. rep., Microsoft Corporation, 2009. 6
- [Mol05] MOLLER T.: A parallel coordinates style interface for exploratory volume visualization. *IEEE Transactions on Visualization and Computer Graphics* 11, 1 (2005), 71–80. 4
- [MRG*01] MOORE M., ROLANDER D., GRAYBEAL B., PHARES B., WASHER G.: Highway bridge inspection: State-of-the-practice survey. *Transportation Research Record: Journal of the Transportation Research Board* 1749 (2001), 73–81. 1
- [New09] NEWLANDS COMPANY: *NC3D, Transportation and Urban Design System*. Tech. rep., Newlands Company, 2009. 9
- [PTSR98] PLAISANT C., TARNOFF P., SARAF A., ROSE A.: *Understanding transportation management systems performance with a simulation-based learning environment*. Tech. rep., Proceedings of ITS'99, Annual Meeting of the Intelligent Transportation Society of America, 1998. 9
- [RFF*08] ROBERTSON G., FERNANDEZ R., FISHER D., LEE B., STASKO J.: Effectiveness of animation in trend visualization. *IEEE Transactions on Visualization and Computer Graphics* 14, 6 (2008), 1325–1332. 6
- [RMSA02] ROBERT W. E., MARSHALL A. R., SHEPARD R. W., ALDAYUZ J.: The pontis bridge management system: State-of-the-practice in implementation and the pontis bridge management system: State-of-the-practice in implementation and development. *Transportation Research Board* (2002). 9
- [Rob07] ROBERTS J. C.: State of the art: Coordinated and multiple views in exploratory visualization. In *Fifth International Conference on Coordinated and Multiple Views in Exploratory Visualization* (2007), pp. 61–71. 4
- [TG02] TAKATSUKA M., GAHEGAN M.: Geovista studio: a codeless visual programming environment for geoscientific data analysis and visualization. *Comput. Geosci.* 28, 10 (December 2002), 1131–1144. 9
- [Tuf90] TUFTE E. R.: *Envisioning Information*. Graphics Press, May 1990. 4, 5
- [Uni06] UNIVERSITY OF FLORIDA MCTRANS CENTER: *McTrans, a transportation planning software*. Tech. rep., University of Florida McTrans Center, 2006. 9
- [Vis08] VISUAL SOLUTIONS INC.: *VisSim, a block diagram language for creating complex nonlinear dynamic systems*. Tech. rep., Visual Solutions Inc., 2008. 9
- [WDSC07] WOOD J., DYKES J., SLINGSBY A., CLARKE K.: Interactive visual exploration of a large spatio-temporal dataset: Reflections on a geovisualization mashup. *IEEE Transactions on Visualization and Computer Graphics* 13 (2007), 1176–1183. 6
- [Wes04] WESEMAN W. A.: *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nations Bridges*. Tech. rep., Federal Highway Administration, 2004. 1
- [WJD*09] WANG X., JEONG D. H., DOU W., LEE S.-W., RIBARSKY W., CHANG R.: Knowledge assisted visualization: Defining and applying knowledge conversion processes to a visual analytics system. *Comput. Graph.* 33, 5 (2009), 616–623. 9
- [WPF*09] WONGSUPHASAWAT K., PACK M., FILIPPOVA D., VANDANIKER M., OLEA A.: Visual analytics for transportation incident datasets. *TRB 88th Annual Meeting Compendium of Papers DVD* (2009). 9
- [WR03] W ROBERT A MARSHALL R. S.: Pontis bridge management system: state of the practice in implementation and development. In *9th International Bridge Management Conference* (Jan 01, 2003). 3
- [XGH06] XIAO L., GERTH J., HANRAHAN P.: Enhancing visual analysis of network traffic using a knowledge representation. In *Visual Analytics Science and Technology, 2008. VAST '08. IEEE Symposium on* (31 2006-Nov. 2 2006), pp. 107–114. 9