



## MAINTENANCE PRIORITIZATION OF BRIDGE STRUCTURES

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**Abstract:** Bridges are aging and deteriorating faster than they are being maintained and replaced, and this is introducing a major problem for bridge authorities across the world. Several studies investigating the trends suggest that the severity is likely to become much worse. As such, there is a large backlog of work that needs to be completed to bring bridge networks up to a desired safety standard. To complicate the matter, the budgets allocated to this type of work are often sparse; and therefore, governing bodies are forced to have to choose how funds are spent. In tackling this problem, appropriate methods for determining the optimum maintenance sequence of bridges within a network must be employed. This has been investigated by several research groups, each proposing their own factors and approaches to be used for classifying the importance of a bridge within a network. This importance can be linked to maintenance optimization as the more important bridges should receive attention first. This paper reviews previously proposed solutions and discusses the similarities and limitations of each method. The current state of the art of maintenance prioritization methods are presented as a framework including a range of periodization factors with various resolution levels that can be optimized for specific networks.

### 1 INTRODUCTION

Throughout the world, authoritative bodies attempt to keep their infrastructure systems at the best possible service level using the funds available to them. This has become extremely important in recent times as the quantity of bridges requiring attention has increased. Both Canada and the United States (US) are prime examples of this problem, which can be illustrated through their infrastructure report cards. Canadian Infrastructure Report Card (2016) categorizes the physical condition of a bridge, ranging from best to worst, into five classes: very good, good, fair, poor, or very poor. 26% of Canadian bridges fall within the bottom three categories. This represents \$13 billion worth of replacement costs, which can also be represented as \$28,000 per household. Although this may seem to be reasonable as 74% of bridges classify as either good or very good, the worry arises from the lack of reinvestment in bridge infrastructure. The current reinvestment rate as of 2016 (Canadian Infrastructure) is below the target range, and as such the anticipated conditions for bridges is declining.

A similar situation is occurring in the US, as bridges scored a C+ on their evaluation as part of the 2017 American Infrastructure Report Card (ASCE 2018). 9.1% of the 614,387 American bridges in 2016 were deemed as structurally deficient, which represents a decrease from the 12.3% in 2007. This may seem to be promising news; however, 40% of the bridges in the US are at least fifty years old, and the average age of bridges is steadily increasing (ASCE 2018). This represents a major mass of bridges that are on the verge of becoming outdated, and in need of replacement. Current estimates show that the US requires roughly \$123 billion in rehabilitation work to their bridges (ASCE 2018). As more and more bridges require work, load restrictions need to be imposed until the funding is available.

These two reports outline the need to properly allocate maintenance funds among bridges as efficiently as possible, while taking into account the importance of a given bridge within a system. Many researchers have investigated bridge prioritization for various reasons, such as maintenance optimization, risk mitigation, and asset management.

Several transportation jurisdictions attempted to address the problem of maintenance prioritization by developing a scoring system that incorporates factors they deemed important to a bridge's condition in comparison to others in a network. In a work completed by Valenzuela et al. (2010), a bridge prioritization index was proposed for the Chilean bridge network. Upon review of current Chilean practices, they recognized the current issues and subsequently generated a list of factors that they felt would better prioritize maintenance. They developed a formula for calculating the index, and as part of this formula, a specific term dealt with a bridge's importance, which had its own equation based on a variety of factors. Another group of researchers, Gokey et al. (2009), worked on developing a prioritization methodology as part of a long-term bridge performance program that was being carried out by the Virginia Department of Transportation (VDOT). This group identified three main categories of attributes, maintenance, economic, and political, which formed the basis of their methodology. Within these categories, were a variety of factors that they felt represented this category well. They compared the economic ranking with the maintenance ranking to form a cross prioritization plot, which helped them select bridges. Political factors were considered separately (Gokey et al. 2009).

In any bridge prioritization methodology, it is important to determine the current physical condition of the bridge. Structural health monitoring (SHM) is an effective way to obtain data on the condition and behaviours of a given structure, while it is in operation. Ni and Wong (n.d.) looked at the use of structural health monitoring methods for the purpose of maintenance management. Their work focussed on implementing SHM on twenty-one bridges, and using the results generated to optimize maintenance operations. They used the data provided by the SHM instruments to analyze the structure, prioritize components and determine required maintenance actions. This system was then able to generate a strategy that could optimize the maintenance options (Ni and Wong n.d.).

Prioritization of bridges has been subject of research from the risk mitigation point of view as well. Golroo et al. (2009) used reliability concepts in their maintenance investment prioritization methodology. This was done by treating the network as a series of links. The importance of a given link was calculated as the reliability of the network when the link is operating normally, minus the reliability of the network when that particular link has failed (Golroo et al. 2009). Decò and Frangopol (2011) used a variety of traffic parameters and associated costs when developing their multi-hazard risk assessment. Although they did not directly discuss these factors in terms of quantifying a bridge's importance, their multi-hazard risk assessment could be used to evaluate the vulnerability and importance of a bridge within a network.

Bana e Costa et al. (2008), also looked risk assessment of bridges, but focussed specifically on earthquake risk mitigation for bridges and tunnels. Their focus on natural hazards such as earthquakes is an important consideration in maintenance planning, as these events have potential to perform severe damage to structures they impact. Much like other papers, they considered economic impacts as a category, but they also incorporated safety in the form of how many people are likely to be on the bridge during a hypothetical earthquake (Bana e Costa et al. 2008). This is helpful in determining how many people may be injured due to an earthquake, rather than how many people will have to take an alternative route as a result of a road closure.

Ray (2007) looked at prioritizing individual bridge components for terrorist threat mitigation. In his work, Ray discussed what previous researchers have done on a system-wide level, which can be helpful for this research. Additionally, his analysis of individual bridge components can help form the basis of a multi-criterion structural health index to be included in a prioritization methodology. Ray (2007) broke the bridge down into many parts and developed a rating system that is unique to each part. This allowed for an overall score to be generated based on his suggested weighting system.

Bush et al. (2013) investigated bridge importance within an asset management context. Although their research was centred on determining appropriate monitoring and inspection techniques based on bridge importance, the principles of their reasoning for priority are still applicable to this research. Many others

also looked into asset management as a means to manage roads and bridges. Trojanová (2014) stressed the importance of using asset management techniques for optimizing maintenance within the Slovakian road networks. Yianni et al. (2016) looked at various deterioration mechanisms due to environmental factors as part of an asset management plan for optimizing railway bridge maintenance.

This paper presents the state of the art for bridge prioritization methods, and discusses their limitations and practicality. In particular, the problem of limited data is to be explored to provide a methodology for jurisdictions who may not be able to acquire all the data required for an ideal determination of bridge priority. As budgets for bridge maintenance are already strict, it is important to consider analysis methods that can be completed to some extent with low input costs. After investigating the various methods and approaches of bridge prioritization, discussion will be created around the common criteria being used, as well as how that criteria can be measured based on the work completed by researchers to date.

## 2 COMPARISON OF CURRENT PRIORITIZATION APPROACHES

The focus of this comparison is to determine what factors have been chosen by researchers to quantify how to prioritize bridges within a network. The current methods used for the maintenance prioritization of bridges use four main categories of parameters, as shown in Figure 1. These parameters are traffic, bridge condition, costs associated with failure, and natural disaster risk.

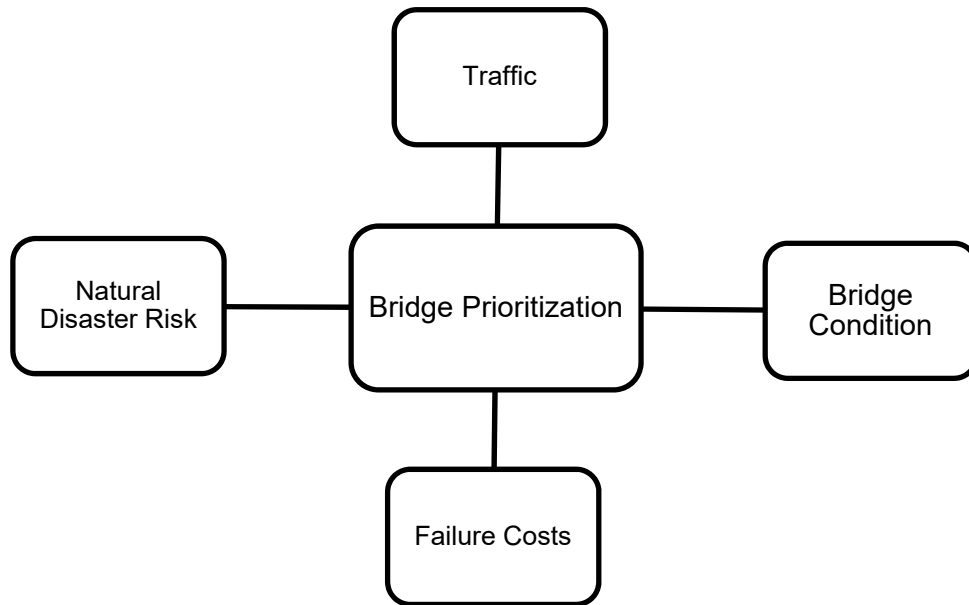


Figure 1: Bridge Prioritization Parameters to Consider

The various factors used by different researchers have been summarized in Table 1. As seen in the table, there are a wide variety of factors considered; however, they can be broadly divided into several main categories. These categories include the ones mentioned in the previous figure; however, it can be noticed that failure costs can be further broken down into direct costs such as the cost of replacing the structure, as well as indirect costs which cover the costs born on society. As discussed in the following sections, the periodization factors in Table 1 can be categorized into one of the four categories shown in Figure 1.

Table 1: Summary of Research on Bridge Prioritization Criteria

<b>Author(s)</b>	<b>Purpose of Research</b>	<b>Factors Chosen</b>
<b>Decò and Frangopol (2011)</b>	Multi-hazard risk assessment (risk based not importance)	Average daily traffic (ADT) Average daily truck traffic (ADTT) to ADT Ratio Average compensation Average detour speed Average vehicle occupancies Average wage Detour length Rebuilding costs Running costs for cars Running costs for trucks Time value of cargo
<b>Golroo, Mohaymany, and Mesbah (2009)</b>	Investment prioritization of transportation network links	Reliability under normal conditions Reliability when link has failed
<b>Wakchaure and Jha (2011)</b>	Bridge prioritization for maintenance planning	Bridge health index Maintenance/repair costs Bridge deck area Bridge age
<b>Bush, Omenzetter, Henning, and McCarten (2013)</b>	Performance data collection and monitoring based on criticality	Replacement cost Average annual daily traffic (AADT) Availability of temporary measures Availability of detour Change in service levels due to detour
<b>Gokey, Klein, Mackey, Santos, Pilluta, and Tucker (2009)</b>	Bridge prioritization within state infrastructure system	Substructure condition Superstructure condition Deck condition Sufficiency rating ADT Future ADT Detour length Budgetary constraints Political perspectives
<b>Ni and Wong (n.d.)</b>	Prioritization of bridge inspection and maintenance	Structural health monitoring methods
<b>Lounis (2006)</b>	Risk based maintenance optimization	Condition rating Maintenance cost User costs
<b>Bana e Costa, Oliveira, and Vieira (2006)</b>	Prioritizing bridges and tunnels in earthquake risk mitigation	Vulnerability Public safety (use per unit time) Emergency response time Local economic impacts Interference with other lifelines
<b>Ray (2007)</b>	Prioritizing bridge components based on terrorist threat mitigation ( <i>what people have used for systems</i> )	Various structural components <i>Function within system</i> <i>Economic importance</i> <i>Symbolic importance</i> <i>Public impact if attacked</i> <i>Cost/time of replacement</i> <i>Likelihood/vulnerability of attack</i>

Table 1: Summary of Research on Bridge Prioritization Criteria (Continued)

Author(s)	Purpose of Research	Factors Chosen
<b>Cheng and Hoang (2014)</b>	Development of an artificial intelligence system for determining bridge priority based on risk scores	Accident potential
		Route importance
		Cost and work required
		Environmental damage
<b>Valenzuela, de Solminihac, and Echaveguren (2010)</b>	Developing an integrated index for prioritizing bridge maintenance	Bridge condition index
		Seismic risk
		Flood risk
		Alternative route
		ADT
		Length and width
		Load restriction

## 2.1 Traffic

It is clear from this table that one of the most important factors in determining a bridge's importance within a network is the volume of traffic it supports. This was commonly encompassed by measuring the ADT, although some were able to obtain an AADT for the area; and therefore, had more accurate information about expected traffic. Decò and Frangopol (2011) went as far as breaking it into truck and non-truck traffic for both volume and economic purposes. This method breaking traffic down into truck and non-truck volumes is used in the Canadian Highway Bridge Design Code, which determines a highway's class based on the separate volumes (CSA Group 2017). Gokey et al. (2009) considered future ADT values in their analysis to incorporate their long-term planning. Bana e Costa et al. (2006) used traffic rates as a measure of people who could potentially be injured as a result of bridges being subjected to earthquakes. This was done by calculating the number of vehicles travelling on a particular bridge per minute; and therefore, provides an estimate of the number of vehicles that could be at risk if an earthquake were to take place. Depending on the availability of traffic data and the depth one wishes to go, it can be seen that traffic can be incorporated at varying levels for the purposes of determining how busy a given bridge is, and subsequently can begin to illustrate how important a bridge is.

## 2.2 Bridge Condition

Another important category of attributes is the bridge's structural integrity. This aspect has been looked at in different ways by different researchers. Where it is a primary aspect, reliability analysis and full structural health monitoring techniques may be used to quantify it as used by Golroo (2009) and, Ni and Wong (n.d.) respectively. However, the most common method of quantifying a structures condition is through the bridge condition index or similar indices, as demonstrated by Gokey et al. (2008), Valenzuela et al. (2010), Lounis (2006), and Wakchaure and Jha (2011). Although the exact basis for determining the bridge condition index may vary among the authors, it can be simply described as an overall bridge condition rating that is determined by visual inspection of the bridge's critical components (Valenzuela et al., 2010). This has been commonly used due to the fact that most transportation jurisdictions perform visual inspections on their structures according to a set schedule. As part of these inspections, a condition index is generated and is therefore readily available to use in prioritizing bridges. Some jurisdictions such as the Ministry of Transportation of Ontario base their condition index on the costs associated with maintenance (Ellis and Thompson 2007). However, this category of parameters is meant to focus on the structural integrity of a bridge.

## 2.3 Costs of Failure

A third main parameter that is commonly considered is the economics associated with the bridge. This can be a broad category as many researchers have looked at quantifying importance using different economic aspects. Generally speaking, the costs are often associated with some form of failure of the bridge, rather than a routine maintenance cost. Failure can be described as total loss of functionality (structural collapse),

but it can also be classified by a decrease in level of service due to the need for maintenance or replacement.

Cheng and Hoang (2014) incorporated costs by looking at the direct costs and work required for a particular bridge if it were to fail. Many of the other authors listed in Table 1 used a cost concept to describe importance by evaluating potential detours. This deals with more indirect costs, as the more convenient a detour is, generally the less additional fuel that needs to be consumed to travel the route. Decò and Frangopol (2011) went much further than the others and broke down all the costs associated with a change in route, including the wages of the drivers and the time value of any cargo that is being transported. Valenzuela et al. (2010) classified economic importance of a bridge based on the main driver of the local economy for different parts of Chile. As an example, a farming-based economy in Northern Chile is less important than a farming-based economy in Southern Chile.

## **2.4 Natural Disasters**

A fourth category that presents itself in several previous studies is the consideration for the effects of a natural disaster. In Bana e Costa et al.'s (2006) work, earthquakes are the primary concern for the research and thus everything is tailored to earthquake risk mitigation. However, other papers such as Valenzuela et al.'s (2010) incorporates both seismic and flood risk into the bridge prioritization index. These factors should be considered where they pose a legitimate threat to the structure and are reasonable given the geography of the area. Edrissi et al. (2013) looked at earthquake disaster management on a city-wide scale; therefore encompassing more than just bridges. However, they mentioned that reliability concepts should be used in classifying importance, and stressed the need for looking after transportation links as they become crucial in post-disaster relief efforts. Peeta et al. (2010) looked at optimizing highway network links by minimizing the cost of traversing from one node to another, while maximizing the connectivity of the network. With respect to bridges in particular, they discussed that the probability of a link failing will decrease as more seismic retrofitting is completed on the bridges in that particular link. A more comprehensive approach to natural hazard risk was covered by Decò and Frangopol (2011) in their multi-hazard assessment.

## **3 LIMITATIONS OF CURRENT APPROACHES**

Although a lot has been done, the proposed solutions often lack practicality or accuracy. There is no clear method that can be relied upon to provide good results for any given jurisdiction, as seen from the variety of factors and varying levels of analysis depth. However, the three main limitations that were encountered were finding a balance between simplicity and accuracy, taking natural hazards into consideration, and developing a method or formulation procedure that suits the area being analyzed.

### **3.1 Finding a Balance**

It can be seen that one of the major difficulties associated with this field is striking the balance between good technical information and analysis and keeping the methodology relatively user-friendly. Several authors such as Valenzuela et al. (2010) and Bush et al. (2013) attempted to determine a method on how to approach this task, but when it comes to their analysis, they simply assigned a score based on a qualitative description of the specific criteria. Although this may be reasonable for some factors, such as assigning a certain score to a given range of traffic volumes, other criteria may not be effectively represented by an individual's qualitative judgement. The reliance on personal judgement also brings a certain bias into the analysis and may cause results to not be consistent among different evaluators.

Another example is the use of a bridge condition index to describe a bridge's condition versus determining the reliability of a given structure by equipping it with structural health monitoring equipment. Condition indices are often generated as part of routine visual inspections. However, these indices are not a direct measure of safety, as explained by the Government of New Brunswick (2018). Therefore, if one wishes to use a safety parameter in their calculation of a bridge's importance, it may be difficult to choose between a readily available measurement that may somewhat predict relative safety levels between bridges, and a more in-depth analysis of the particular structure. On the other hand, for jurisdictions with large quantities

of bridges, performing a structural analysis on every bridge would be tremendously expensive and time consuming.

### **3.2 Dealing with Natural Hazards**

Taking natural hazards into account can also be a challenge as illustrated in Valenzuela et al.'s research (2010). Chile is extremely susceptible to earthquakes and as such they placed a strong importance on seismic risk. However, attempting to quantify seismic risk was one of their biggest challenges and in the end they were not satisfied with the level of analysis they were able to achieve. Impacts of natural hazards such as earthquakes often depend on geography and the structure itself. Therefore in order to properly assign such a rating, a detailed analysis must be completed for each bridge (Valenzuela et al. 2010), which can become quite time-consuming and require a great deal of resources. In New Brunswick, seismic risk may not be as important as it would be in Chile, but other natural hazards such as flooding can be present and require detailed analysis to fully understand the impacts on an individual bridge.

This category is becoming increasingly important as major weather events become more severe and frequent in our changing climate. Structures currently in place were likely designed to codes that did not capture the potential magnitude of future weather events. Increased snowfall, extreme winds and rain, and overall climate changes have the potential to pose serious threats to the current bridge infrastructure. Therefore, once again there is a need to ensure maintenance is carried out to bring structures up to the appropriate standards to prepare for the future.

### **3.3 Formulating a Prioritization Index**

Choosing appropriate factors and determining their relative importance may also become a challenge as it can be seen from Table 1 that there still exists a variety of preferred criteria. In developing a priority index it is important to consider how important each of the criteria are in relation to each other. Valenzuela et al. (2010) presented their approach for determining importance among factors, which consisted of surveying engineers who work in the field of bridge maintenance and asking how important they rank each criteria. This led to a list of desired factors and subsequently a weighting among factors which could then be incorporated into an equation for calculating a priority index (Valenzuela et al. 2010).

Gokey et al. (2009) used a similar approach of discussing factors with an expert in the field of bridge maintenance. However, this may lead to some bias as only one expert was consulted. In other works, it is not as evident as to how certain factors were chosen and why they were or were not weighted. Some groups relied on factors that were strictly qualitative and as such, assigning a number to these factors was not always justifiable. However, the problem of simplicity versus complexity arises again as some factors could not be reasonably quantified without just assigning a subjective score.

## **4 MAINTENANCE PRIORITIZATION**

Although it is easy to point out flaws or discrepancies in current practices and upcoming methodologies, the reality of the fact is that these methods are being carried out with limited information available and under limited resources. It would be extremely costly for the operators and the departments of transportation to continuously collect, maintain, and process the necessary detail information regarding their bridge inventory. As the budget for maintenance is already quite strict, the low costs associated with better planning would be easily justifiable in comparison of the costs associated with the maintenance itself. Aside from simply collecting more data, some criteria require in-depth analysis and calculations in order to properly quantify them.

In an ideal world, each of the factors chosen for a particular method of prioritizing bridges would be explicitly determined via appropriate data collection or analysis. This would eliminate the possibility of subjective bias or inconsistencies among the various qualitative ways of carrying out the methodology. However, even making small changes to improving the accuracy of various aspects may help to incrementally improve bridge maintenance management. In order to illustrate the various milestones that can be made in terms of data collection, three figures (Figure 2, 3, and 4) have been provided to show an increasing level of data

accuracy among three of the main categories (traffic, bridge condition, and economics) of bridge prioritization factors.

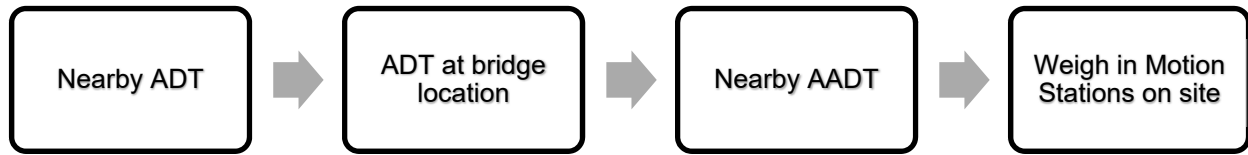


Figure 2: Traffic Data Ordered by Increasing Accuracy

Bridges must be maintained to operate safely considering the traffic volume and type that use them. Therefore, in maintenance prioritization of bridges within a network, it is crucial to have an accurate understanding of the traffic that uses that bridge. ADTs represent short term traffic volume averages, which become more accurate as the recording site becomes closer to the bridge of interest. An AADT can be determined with the use of a permanent count station, which once again becomes more accurate as the station gets closer to the bridge being studied. Weigh in motion stations provide the most accurate data, as they are able to break down traffic volumes into non-truck, truck, and overweight truck requiring permits. The advantage of these permanent weigh in motion stations is that in addition to breaking down traffic volumes, they allow users to monitor fluctuations in traffic over time and take the changes into consideration when planning maintenance.

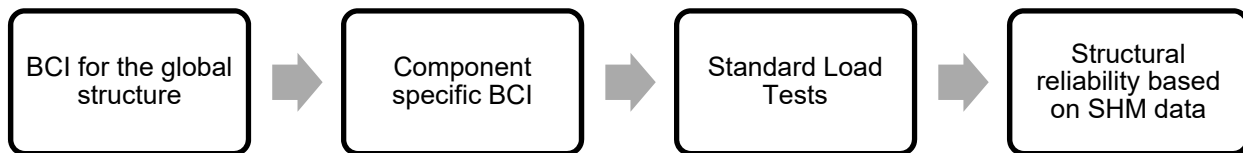


Figure 3: Bridge Condition Determinants Ordered by Increasing Accuracy

In order to determine the condition assessment of bridge structures, one must inspect or monitor the structure in some way to determine its current state. Therefore, one of the easiest ways to improve accuracy of bridge condition data is to increase the frequency of inspections. Visual-based inspections and subsequent determination of a bridge condition index (BCI) seems to be the least accurate as previously mentioned that it does not necessarily predict safety. However, breaking the index into separate indices for specific bridge components should provide a better picture of the condition of a bridge. These components could include items such as the superstructure, the substructure, and the wearing surface. However this could be broken down even further if time and funds permitted. Standard load tests can be used to monitor specific components subjected to a standard load to determine the adequacy of the member (CSA Group 2017). The ultimate level of bridge condition determination would involve structural health monitoring (SHM) techniques and subsequent calculation of a reliability index based on the present condition of the bridge. As technology becomes cheaper, and therefore SHM instruments become more practical to implement, continuous monitoring of structures will provide an accurate way of classifying the current condition of a bridge.

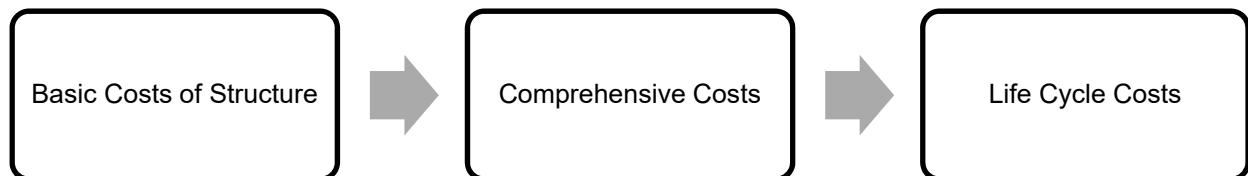


Figure 4: Economic Details Ordered by Increasing Accuracy

The economic aspects associated with a bridge failure are very important when determining how important a bridge is. However, it can be seen in Figure 4 that this is a broad category that can require a great deal



of analysis to achieve a certain level of accuracy. Basic estimates could include the cost of the structure in terms of its present worth. Assuming that failure of the bridge results in the implementation of a detour for the traffic on that link, it is important to also consider how much longer the trip becomes due to that link of the network being out of commission.

These aspects can be further improved by taking a more comprehensive approach and considering the replacement costs of the existing structure, and specific costs related to imposing a detour. Ultimately, completing a full life cycle analysis of maintaining and replacing the structure would provide the most accurate assessment of the structure costs. This can be taken one step further by including societal costs. These costs would not only include the taxpayer costs associated with the lifecycle analysis, but also costs indirectly associated with the structure. These costs can include fuel, time, and depreciation costs associated with a detour, as well as impacts to businesses and communities due to rerouting of traffic. Analysis for determining likely injuries or deaths in the case of a collapse could also be included as done in Bana e Costa et al.'s work (2008). As one may imagine, these costs can become extremely difficult to calculate for any given bridge; therefore, a whole new challenge exists for considering these on a network-wide basis.

Although some of these ideas are not achievable on a short-term time scale, it is important for the bodies that govern roads and bridges to recognize this need and gradually implement changes to better their maintenance systems. As a general relation, in terms of maintenance optimization, a bridge's Bridge Prioritization Factor (BPF) can be described as shown in Equation 1.

[1]  $BPF \propto TD, 1/BC, E, ND$

Where I represents the importance, TD represents the traffic demand, BC represents the condition of the bridge, and E represents the costs associated with a bridge failure, and ND represents the risk associated with a natural disaster. Researchers are currently investigating detailed formulation of both the equation as a whole, as well as the individual parameters.

## 5 CONCLUSION

This paper investigated an efficient method of bridge prioritization, specifically for maintenance planning and optimization. As a result, a summary of current approaches has been created and assessed. It was found that although individual factors may vary, bridge prioritization generally falls within four main categories of attributes: traffic volume, bridge condition, economics, and natural hazards. It was noticed that although many researchers have looked into this field, some common limitations exist among the different proposed methodologies. The first limitation is that in completing a bridge prioritization assessment, it can be difficult to strike a balance between keeping things practical and capturing accurate data to base decisions on. The issue of limited resources often pushes these methods to remain simple, as more detailed analysis is generally accompanied by much longer analysis periods and subsequently a greater need for resources.

With respect to helping a jurisdiction decide what to look into when taking on bridge prioritization, it is important to ensure that the four main categories of factors are considered and adequately represented. Representative factors should be quantitative if possible to avoid the bias and potential inconsistencies associated with qualitative assessments. When considering a multi-hazard assessment approach it is important to only consider ones that are reasonable given the location of the bridge in question. Although challenges lie in quantifying the effect of these risks on bridge infrastructure, it leaves lots of opportunities to investigate this topic. In doing so more effective maintenance prioritization methods can be developed, which will help to optimize planning and spending on bridge maintenance.

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