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Short-line railroad management system for bridge prioritization

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Abstract

Purpose – Limited funding to maintain and preserve short-line railroad (SLRR) bridge infrastructure requires that important priority decisions be made on an annual basis. The compartmentalized, dispersed, and diverse nature of many SLRR owners and operators is such that there is a need for a coordinated and centralized effort to evaluate the state-wide system as a whole, to ensure the most effective overall resource allocation and also identify assets that either outperform predictions or consume disproportionate levels of resources for maintenance and operation, allowing for review of design and construction practices. The purpose of this paper is to examine the state of the art for railroad bridge population management and resource allocation decisions and to develop a state-wide SLRR bridge prioritization methodology, to be used as a tool by a state agency to assist in allocating limited public funding for bridge maintenance, rehabilitation and replacement activities.

Design/methodology/approach – A literature review examining the state of the art of railroad bridge population management and resource allocation decisions was conducted, which provided the foundation for the development of a bridge prioritization algorithm. A state-wide survey was conducted to develop a bridge database. A detailed evaluation of a statistically significant sample of bridges was conducted, to determine the structural and maintenance needs and preservation status of sub-populations. The research team developed methodologies, applicable to the entire population, to develop a ranking of bridge preservation candidates.

Findings – A risk-based prioritization algorithm is proposed to assign a relative risk score to each bridge in the population. The algorithm provides a management tool for making more effective maintenance and preservation decisions. Additionally, the bridge database allows managers to examine sub-populations according to structural parameters to evaluate performance.

Originality/value – The revisable, modular framework of the prioritization algorithm provides a simple, effective and versatile tool for asset management and evaluation. The present proposal of this new prioritization methodology for SLRR bridges is a valuable tool for agencies faced with making rational decisions with limited information. Such a methodology does not currently exist in the literature and is of significant interest to short-line owners/operators and state transportation agencies.

Keywords United States of America, Rail bridges, Railways, Maintenance programmes, Decision support systems, Database management, Asset management, Risk assessment

Paper type Research paper

1. Introduction

Bridges represent a significant proportion of short-line railroad (SLRR) assets, therefore, resource allocation to bridges must be managed effectively to ensure safe and economical operation above the minimum desired level of service. Effective

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statewide management of bridge assets must combine engineering and economics principles in order to preserve and improve SLRRs as a statewide transportation system to ensure the economic health of the state and region they serve. With well-defined decision criteria, effective asset management system provides the framework by which managers identify maintenance and repair priorities and timing of activities when funding needs exceed available funds and also identifies assets that either outperform predictions or consume disproportionate levels of resources for maintenance and operation, allowing for review of design and construction practices.

Of critical importance to the development of a useful management plan is a complete and detailed bridge population database, however, no central agency maintains a national, state, or regional inventory of railroad bridges comparable to the Federal Highway Administration (FHWA) National Bridge Inventory (NBI) of highway bridges. Each railroad maintains, to some degree, an inventory of bridges under its jurisdiction. Recognizing this as an important infrastructure issue, the American Short Line and Regional Railroad Association (ASLRRA) has followed the lead of the Federal Railroad Administration with bridge safety and management initiatives. In November 2007 the ASLRRA created a bridge safety task force to address several maintenance issues with the goal of developing new management programs (Boardman, 2008). In addition, the Rail Safety Improvement Act of 2008 (Congress of the United States of America, 2008) will expedite the process by which SLRRs adopt bridge management plans.

Application of limited resources for design and construction of upgraded or new assets must also be guided by the vast experience gathered and available through a management system. Feedback from such operation and maintenance to design managers/engineers enables the consideration of relevant maintenance-sensitive parameters in future designs and detailing. Construction managers will also become aware of any ineffective construction approaches that aggravate future operation and maintenance.

1.1 Objectives

The primary objectives of this study were to examine the state-of-the-art for railroad bridge population management and resource allocation decisions and to develop a statewide SLRR bridge prioritization methodology to be used as a tool by a state agency to assist in allocating limited public funding for bridge maintenance, rehabilitation and replacement activities. The research team conducted a statewide survey of 77 SLRRs managing over 1,100 bridges to establish a bridge population database containing both inventory and condition information. Using field survey results and published literature, the research team developed methodologies applicable to the entire population to establish a bridge management prioritization algorithm. This paper presents overview results of the project literature review and a proposed, risk-based, prioritization algorithm that define and quantify both the probability and consequences of bridge failure.

2. Infrastructure management studies

The primary objective of a successful bridge management system (BMS) is to ensure the overall safety of a network to guard against catastrophic failures that could result in loss of life, adverse environmental impacts, and disruption to the rail system. A management system must also provide decision support to both preserve the current value of assets by ensuring that bridges function at required levels of service and ensure that strategic investments for rehabilitation and replacement are made at optimal times with intelligent design and construction. The basis for network safety assurance and network decision support stems from the collective knowledge of individual bridge inventory and condition data for all bridges within the network population.

2.1 Asset management systems

Asset management combines engineering principles and economic theory. The primary purpose is to assist managers in establishing systematic, cost-effective strategies to ensure current and future safe function at or above acceptable condition levels. It provides the decision-making tools for planning what maintenance and repair activities should be taken, when such actions should be taken, what design and construction is to be adopted, and how to prioritize these actions when funding is limited. Additionally, a management system provides important information to design and construction engineers related to performance and maintenance of not only the entire bridge, but also its component parts and details.

2.1.1 Highway BMS. Two commercial BMS are Pontis and BRIDGIT. Pontis is a powerful BMS developed for the FHWA (Godzwon, 2004) and is the predominant BMS employed by state departments of transportation. Pontis is a complete system that stores and analyzes inventory and inspection data to assist transportation agencies in managing bridge inventories and making decisions about preservation and functional improvements for their structures. BRIDGIT (Hawk, 1999) is a BMS software package developed under the AASHTO-sponsored National Cooperative Highway Research Program. It is intended to meet the needs of state, local, and other bridge agencies by providing guidance on network- and project-level management decisions. The architecture of BRIDGIT consists of five modules: inventory; inspection; maintenance, rehabilitation, and replacement; analysis; and models.

A BMS software application appropriate for municipal-size inventories is discussed by Kriviak (1999). Database functions are separated into static (inventory) and dynamic (visual inspection) modules that are suitable for bridge and culvert structures. The database modules are structured to include both essential and non-essential categories. Similar to the National Bridge Inspection Standards (NBIS), a numerical nine-point visual condition rating system is used for inspection data. Data records can be maintained for both representative and worst condition of each inspected element. Analysis routines are provided that compute structure rating values, establish network-wide management strategy options, and facilitate detailed site-based present value computations.

Gralund and Puckett (1996) developed a highway BMS for local-level, rural agencies in Wyoming with many applications to SLRR bridges. The program design is separated into two phases: first, inventory and second, prioritization. The prioritization scheme is based on a deficiency point model that can be refined to reflect user preferences. Deficiency points for the structure as well as its components are calculated, thereby providing a quantitative measure of the bridge condition.

2.2 Risk management and prioritization

Prioritization for determination of resources to be allocated to a population of assets requires some level of risk management strategy (Lowe and Andrews-Phaedonos, 2002). The fundamental and standard definition of risk within this context is the product of the probability of failure of an asset times the consequence of the failure:

$$\text{Risk} = \text{Probability} \times \text{Consequence} \quad (1)$$

2.2.1 Probability of failure. Zayed *et al.* (2007) studied methods of risk assessment for bridges with unknown foundations. The principles and approach are applied to highway bridges; however, the ideas are directly applicable to the present study, not only as it relates to foundations but other aspects of risk as well. Zayed *et al.* (2007) proposes a methodology leading to a risk index, R, that is a function of several factors and permits a prioritization: "This index was developed primarily to transfer the subjectivity of risk parameters into quantitatively determined values using the analytical hierarchy process (AHP) developed by Saaty (1980)." The determination of risk is based on the following formulation:

$$R = \sum_{i=1}^{n} W_i V_i(x_i) \tag{2}$$

where R is the risk index, W_i is the weight for each risk factor i using the eigenvalue method, $V_i(x_i)$ is the worth score for each risk factor (x_i), x_i are the different risk factors. The Zayed *et al.* (2007) proposal identifies, in its fundamental form, a probability of failure but does not consider consequences.

Lowe and Andrews-Phaedonos (2002) addresses probability of failure as a function of factors for loading (LF), resistance (SF), condition (CF), inspection (IF), and exposure (XF). As a result, the probability of failure, in relative terms, is determined as:

$$P_f = LF + SF \times CF \times IF \times XF \tag{3}$$

Gralund and Puckett (1996) explain that simplistic systems may be prioritized by a standard ranking formula:

$$\text{Rank} = \sum \{K_i f_i(a, b, c...)\} \tag{4}$$

where K_i is the weight factor for each criterion considered; $f(a, b, c \ldots)$ are priority ranking formulas; a, b, c are bridge condition or goal parameters, which is very similar to the formulation presented by Lowe and Andrews-Phaedonos (2002).

A risk assessment of Pennsylvania Department of Transportation (PennDOT) owned bridges (PennDOT, 2007), was developed to establish risk levels for certain highway bridge populations and establish mitigation measures. PennDOT (2007) selects several focus areas of most significant influence on risk, those being identified as physical condition, load capacity, scour, impact damage/over height vehicle, and fatigue. Risk levels were established as high, medium, and minor based on BMS ranking values considering two levels of risk: aggregate risk and structurally deficient risk.

2.2.2 Consequence of failure. Lowe and Andrews-Phaedonos (2002) addresses consequences of failure as a combination of separate factors: human factor (HF), environmental factor (EF), traffic access factor (TF), economic factor (NF), and road class (RF). As with the probability of failure determination discussed, the determination of the consequence of failure employs a relative approach, considering a subjective scale as applied to a family of important factors. Typically this relative measure is the approach used for a prioritization where a detailed cost-magnitude calculation would not be feasible and a relative ranking is the objective in any case.

Stein *et al.* (1999) present a methodology for scour risk evaluation that follows the established fundamental approach for risk discussed here. Items important to scour potential are type of span (simple or continuous), type of foundation (piles, floating spread, or unknown), NBI condition ratings (adequacy of waterway, channel protection, and substructure condition), and scour evaluations done in the field. A discussion of consequences as a result of scour failure is presented by Stein *et al.* (1999); however, the discussion applies to any failure cause. The determination of consequence is fundamentally based on economics or the expected value of the loss. This includes the cost to replace the bridge, the cost to maintain traffic flow without the bridge, and the value of time lost utilizing alternate routes. Not considered, but potentially significant consequences are collateral property damage, injury, and death.

3. Prioritization algorithm development

The proposed SLRR bridge prioritization scheme has been developed under a broad framework for risk assessment of the bridge infrastructure. Recalling the fundamental definition of risk equal to the product of the probability of failure of an asset times the consequence of the failure, where $0 < \text{probability} < 1.0$ and $0 < \text{consequence} < 1.0$ are defined in subsequent sections. Investigating each of the two components of risk (probability and consequence) separately:

$$\text{Risk} = \left\{ 1 - \sum_{i=1}^{n} \left[W_i \frac{(PP)_i}{N_i} \right] \right\} \times \left\{ \sum_{i=1}^{n} \left[W_i \frac{(CP)_i}{N_i} \right] \right\} \tag{5}$$

where $(PP)_i$ is a probability parameter, $(CP)_i$ is a consequence parameter, N_i is a normalizing value, and W_i is an assigned weighting factor corresponding to the particular probability or consequence parameter that reflects the relative importance of the associated parameter in the risk evaluation.

Neither probability nor consequence is readily calculable in absolute terms; however, a relative assessment can be made. Probability of failure is directly related to loading magnitudes, load frequency, structure age and condition, maintenance and inspection intervals, structure type, and rehabilitations. Consequences of failure are directly related to human safety, environmental safety, and economic loss, including loss of revenue for the SLRR, the connecting railroad, and customer(s); loss of structure; and loss of rail cars or locomotive. Each of the probability and consequence factors relevant to the prioritization is ranked using a pre-established, relative scale. In addition, a weighting for each factor addresses relative importance.

A complete risk analysis requires an extensive and comprehensive study, including a detailed analysis of every bridge in the population, and would require resources not currently available. Therefore, the present study selected several factors with significant influence on risk to define the probability and consequence of failure which are superstructure condition, substructure condition, load capacity, scour potential, and fatigue susceptibility to assess probability of failure and human factors, environmental factor, economic factor, and railroad classification factor to assess consequences of failure. Associated numerical levels for each were established to be consistent with previously published studies and consistent with the fidelity of available information as it corresponds to the parameter.

3.1 Probability of failure

Probability of failure is evaluated as an accumulation of the proposed probability parameters (PP_i) including bridge reserve (R), substructure condition (Sb), scour (Sc), and fatigue (F) where the parameters are defined in the following sections. Therefore, the probability of failure is defined as follows:

$$\left\{1-\sum_{i=1}^{n}\left[W_i\frac{(PP)_i}{N_i}\right]\right\}=\left\{1-\left[\frac{W_RR}{1}+\frac{W_{Sb}Sb}{4}+\frac{W_{Sc}Sc}{4}+\frac{W_FF}{10}\right]\right\} \qquad (6)$$

Because the SLRR bridge prioritization is a relative measure between all structures in the bridge population rather than an absolute measure, the proposed scheme identifies, and assigns relative magnitudes for each bridge factor to be considered as described in each section addressing these parameters.

3.1.1 Bridge reserve (R)

R is a function of four interrelated parameters: structural capacity (C), loading (L), superstructure condition (Sp), and age of bridge (A). Because these four parameters are interrelated and all influence the reserve strength of the bridge, it is necessary to define this interrelationship as it affects the probability of failure. For the purposes of this study, the bridge reserve strength is defined as follows:

$$R=\left\{\left[\frac{C}{L}\right]\times\left[\frac{Sp}{10}\right]\times\left[\frac{40}{A}\right]\right\} \qquad (7)$$

where the determination of the variables C, L, Sp, and A is discussed in detail.

Bridge load rating factor (C/L): the ratio of C to L, defines the bridge load rating factor. Capacity is determined in accordance with the American Railway Engineering and Maintenance-of-Way Association (AREMA, 2008) for the maximum equipment load expected to cross the bridge. Historically, the Cooper E series design load was considered for rating analyses, however, the present gross car weights (GCW) and axle configuration can, for certain bridge configurations, produce controlling load effects, especially in bridges <50 ft in length. Many Pennsylvania SLRRs surveyed considered bridge ratings in terms of GCW, therefore, the research team considered load rating factors (C/L) in terms of a typical 286,000 pound GCW equipment load.

Superstructure condition (Sp): condition rating is based on an inspection and engineering evaluation. Bridge condition data provide a direct indication of the overall state of the bridge and, therefore, are used in the determination of probability of bridge failure. Superstructure condition directly relates to the bridge reserve and is a critical factor for prioritization. The objective of the present study is to evaluate SLRR bridge condition on a system-wide basis; therefore, a uniform condition rating system is proposed. The qualitative, numerical rating system is based on a ten-point scale presented in Table I, similar to that used by the NBIS for highway bridge evaluation.

Bridge age (A): A is an important parameter in evaluating the relative prioritization of the bridge population in the database, in particular, R. Bridge age directly influences the overall reserve capacity and the ultimate prioritization ranking as compared to other bridges, assuming a similar maintenance program over the life of the bridge. It is

Table I.
Assigned values of superstructure condition (*Sp*)

	Description									
	Extremely deteriorated	Very heavy deterioration	Heavy deterioration	Significant deterioration	Moderate deterioration	Very moderate deterioration	Slight deterioration	Very slight deterioration	Recent construction	New construction
Assigned value	1	2	3	4	5	6	7	8	9	10

recognized that a bridge constructed in the most recent 40 years is of relatively modern construction. *A* is reported in the SLRR database in terms of years.

3.1.2 Substructure condition (Sb). Of the many parameters involved in a risk calculation and the necessary probability evaluation under discussion here, the condition of the substructure holds the highest uncertainty. Due to the nature of substructures and the unobservable, buried elements, a visual inspection may not reveal significant information about the original construction or status of the existing substructure. Typically, original or reproduced substructure drawings are not available; therefore, any substructure condition rating can only be broadly estimated at best and must be largely presumptive. Certain aspects of deterioration may be readily observable such as abutment stem spalling or evidence of settlement; however, much of the structural assessment desired is not possible. With this background in mind, it is not justifiable to narrow the condition categories to a level of refinement similar to that of the superstructure (Table I), where magnitudes of 1 through 10 are assigned values. Therefore, four categories have been identified for the assigned value of *Sb* as presented in Table II, which is consistent with the fidelity of the information that can be obtained.

3.1.3 Scour (Sc). The proposed methodology to include the probability parameter of scour recognizes that foundation design and construction, as well as current scour condition information, is very limited for SLRR bridges. Scour potential requires a detailed, hydraulic analysis at the bridge site, normally with numerical simulations of the waterway flow and with predictions of mean recurrence intervals for flood events. The parameters that most influence scour and its influence on probability of failure are the current and observable level of scour and the magnitude and velocity of water flow at the foundations. Therefore, a four-level, subjective evaluation is proposed, as presented in Table III, making use of readily observable features at each bridge that directly influence scour potential. Assigned values range from "no water and scour not observed" to "scour present."

Bridge failure as caused by scour is dependent on certain physical characteristics of the bridge itself such as structural redundancy and foundation type. Stein *et al.* (1999) propose adjustment factors to account for structural redundancy of continuous, multi-span bridges as well as foundation type. Generally, this information is not currently

Table II.
Assigned values for substructure condition (*Sb*)

	Description			
	Poor Significant spalling, large cracks, settlement	Fair Significant cracks, some spalling	Good Minor deterioration	Excellent Like new condition
Assigned value	1	2	3	4

Table III.
Assigned values for scour condition (*Sc*)

	Description			
	Scour probable or present	Scour not observed, large river	Scour not observed, small stream	Scour not observed, no water
Assigned value	1	2	3	4

available for SLRR bridges; however, as future SLRR bridge inspections are completed and the compiling of information in the database increases, a more reliable forecast of scour will be possible.

3.1.4 Fatigue (F). Fatigue is a cumulative effect that grows more significant with time, assuming that the structure continues to be cyclically loaded. Each bridge may contain one or more fatigue-prone details with the potential to develop a fatigue crack, resulting in failure or collapse of the bridge. Bridge type (e.g. steel-deck plate girder or concrete slab), drawn from a database, can imply fatigue category due to the relative consistency of railroad bridge design and construction across types. Fatigue detail categories are defined by AREMA (2008) and listed in Table IV. For the purposes of prioritization, the most severe AREMA fatigue detail category on the bridge is assigned to that bridge.

A complete fatigue evaluation depends on both the fatigue prone details and the loading history – both magnitude and frequency, or number of cycles. However, load history is typically not known or retrievable for SLRR bridges, therefore, bridge age is assumed to be directly related to the number of load cycles for the purpose of fatigue evaluation:

$$F = \text{Assigned value} \times \frac{A}{100} \tag{8}$$

where the assigned value is taken from Table IV and A is the bridge age in years as defined. The underlying principle of number of cycles is incorporated indirectly here by assuming that cycles are directly related to structure age and that the relationship is linear. A normalizing value of 100 years has been adopted due to the range of bridge ages in the population.

3.1.5 Assigned weights for probability of failure. Assigned weights, or levels of importance, for each structural item that relates to probability of failure discussed are presented in Table V. The relative magnitudes of the weighting factors are fundamentally policy decisions to be determined by the responsible governing agencies or management; however, the weighting shown reflects the results of the literature review (Gralund and Puckett, 1996; Saaty, 1980) for the present study and recommendations by the authors.

A hierarchy was established based on quality and completeness of data and comparative judgment of how each parameter relates to the primary objective of the study; prioritizing bridge maintenance, rehabilitation, and replacement activities. Fatigue is at the bottom of the hierarchy because load history is not known with high

	Description									
	F	E′	E	D	C″	C′	C	B′	B	A
Assigned value	1	2	3	4	5	6	7	8	9	10

Table IV.
Fatigue category and corresponding assigned value

Reserve (W_R) (%)	Sub-structure condition (W_{Sb}) (%)	Scour (W_{Sc}) (%)	Fatigue (W_F) (%)	Total (%)
45	30	20	5	100

Table V.
Recommended weighting factors for probability parameters

confidence, most SLRR bridges pre-date welded construction, and due to the localized, non-catastrophic nature of fatigue prone details. Scour is a significant factor; however, current scour condition, foundation type, and scour susceptibility information is very limited for SLRR bridges thus scour is next in the hierarchy. The importance of substructure condition follows scour in the hierarchy because, while some aspects of substructure condition are presumptive, often signs of distress are readily observable, such as settlement and component relative displacement. Additionally, substructure repairs typically require greater resources as compared to fatigue and scour. At the top of the hierarchy is reserve. An objective of the study is to ensure that SLRR bridges are capable of supporting standard freight traffic loads to ensure viability of the SLRR in the network. Therefore, *C/L* and *Sp*, constituents of reserve are highly important and they are typically known with the greatest confidence.

Bridge risk values, or relative probability of failure, are computed on a relative basis using a weighted calculation of the assigned values between 0 and 100 percent.

3.2 Consequence of failure. The failure of any bridge may have significant consequences, ranging from loss of life to the disruption of freight traffic to the costs associated with environmental clean up to repair or reconstruct the structure. To quantify consequences of bridge failure, the proposed consequence parameters $(CP)_i$ considered in this study are human (*Hu*), environmental (*En*), economic (*Ec*), and railroad classification (*Rc*). These parameters are defined and discussed in the following sections. Therefore, the consequence of failure is defined as follows:

$$\sum_{i=1}^{n}\left[\frac{W_i(CP)_i}{N_i}\right]=\frac{W_{Hu}(Hu)}{10}+\frac{W_{En}(En)}{10}+\frac{W_{Ec}(Ec)}{1}+\frac{W_{Rc}(Rc)}{1.2} \qquad (9)$$

3.2.1 Human (Hu). *Hu* incorporates the impact on human safety as a result of the failure of the structure. It is extremely difficult to assign an appropriate *Hu* with confidence because there are many contributing issues that depend on information that is either not known or is known with little confidence for the majority of SLRR bridge in the project database. However, because the prioritization of bridges is a relative comparison, the absolute value of human safety consequence is not needed. The question to be addressed through *Hu* is a comparison between potential consequence scenarios that might be presented at any given bridge. *Hu* is investigated by considering the immediate and direct effect of bridge collapse and the secondary or indirect effect of bridge collapse on human safety.

The immediate consequence of a failure on human safety accounts for the safety of individuals on board the train as well as individuals within close proximity to the bridge at collapse. Because the present study examines freight SLRRs, it is expected that the only individuals on board are train personnel. Additionally, it is assumed that all trains have approximately the same crew size and that any bridge failure would affect their safety equally. This component of the human factor then becomes a constant and has no relative influence, and thus does not need to be considered. However, the safety of individuals that may be in close proximity to the bridge, such as pedestrians and traffic under the bridge, must be considered. The proposed approach to quantifying the human consequence of individuals in proximity to a bridge is based on highway classification. A five-level scale is proposed, as presented in Table VI, consisting of a numerical value assigned to each bridge on the basis of highway or railroad classification passing under an SLRR bridge. The magnitude for each classification is based on proportions of individuals in the vicinity at an arbitrary point in time based on the average daily traffic, number of lanes, and/or likelihood of pedestrians present. *Hu* values provided in Table VI are applicable to all SLRR bridges. A bridge that does not cross-over a roadway is categorized as "other" and receives an assigned value of 1 to represent collateral human safety consequence.

The secondary, or indirect, effect of bridge failure on human safety would account for the potential human consequences associated with a train incident and exposure to transported contents. These effects are highly dependent on the hazard level and type of commodity transported and the potential magnitude of human exposure if a bridge failure occurred. A rational quantification of the potential relative human consequence from this secondary effect requires knowledge of shipped commodity hazards, shipped commodity quantity in any given shipment, frequency of shipping, and population density within some critical radius of the structure. This information is often not known for SLRRs; therefore, it is assumed that the consequence for all bridges is the same.

3.2.2 Environmental (En). Bridge failure can result in negative, permanent consequences on the environment. Similar to *Hu*, it is not possible to predict environmental consequence with high certainty. The feature that most influences environmental consequence potential is the nature of the bridge crossing – bridges crossing large bodies of water hold the greatest potential for negative environmental outcomes and bridges crossing a dry land mass hold a very low potential. A five-level scale is proposed, as presented in Table VII, consisting of a numerical value assigned to each bridge on the basis of water features passing under an SLRR bridge. The magnitude is based on a qualitative review and is assumed to represent the gross environmental impact of bridge failure.

3.2.3 Economic (Ec). *Ec* represents the cost of bridge failure on not only the bridge owner and operating railroad, but also the customers and consumers served. *Ec* can also include direct and indirect costs to other private, local, and state agencies. Economic consequences associated with bridge failure include loss of existing bridge value, loss of equipment and freight value, cost associated with alternate freight transportation modes, cost of cleanup, cost of reconstruction, legal costs, and loss of revenue opportunity. The quality and completeness of existing data does not facilitate a focussed economic analysis. Instead, it is recognized that a relationship exists between the above-listed costs, a function of bridge length factor, *Lb*, and annual gross

	Description				
	Principle arterial	Minor arterial/ passenger railroad	Collector road/ class 1 railroad	Local road/ SLRR	Private road/ other
Assigned value	10	8	6	3	1

Table VI. Assigned values for human consequence parameter, *Hu*

	Description				
	Major river	Minor river	Creek	Run	Normally dry/other
Assigned value	10	8	6	3	1

Table VII. Assigned values for environmental (*En*) freight tonnage, *Tgf*. Therefore, *Ec* is defined as:

$$Ec = \frac{W_{Lb}(Lb)}{500} + \frac{W_{Tgf}(Tgf)}{5} \tag{10}$$

where *Lb* and *Tgf* are a function of bridge length and gross freight tonnage, respectively, and the author recommended weight factors, W_{Lb} and W_{Tgf}, are presented in Table VIII. These parameters are defined and discussed later.

Bridge length factor (*Lb*): *Ec* is a function of *Lb* based on the understanding that the consequences of a long bridge failing are more substantial that of a short bridge failing. The proposed, general relationship between *Lb* and total bridge length is presented as:

$$Lb = \sqrt{\frac{L_T^2}{n_s}} \leqslant 500 \tag{11}$$

where L_T is the total bridge length (feet) and n_s is the number of spans in the bridge. Equation (11) was developed to account for the range of span lengths and construction types in long, multi-span, multi-superstructure type bridges. Individual span configuration is not known for many SLRR bridges in the project database, therefore *Lb* as a function of total length and number of spans is the most accurate assessment possible. Additionally, an upper bound value of 500 is placed on Equation (11) to limit *Lb* values from non-typical bridges.

Gross freight tonnage (*TgF*): annual freight tonnage is expressed in millions of gross tons (MGT), which provides an indirect measure of the economic consequence of bridge failure. Absent more detailed freight information, the economic consequence of a bridge failure on a SLRR with a high MGT is assumed to be more significant than a bridge failure on a low MGT SLRR:

$$Tgf = \mathrm{MGT} \leqslant 5 \tag{12}$$

A limiting value of 5 MGT has been established to prevent high-tonnage bridges from completely dominating all other parameters and bridges. Also, neither unit weight nor value per unit weight is constant for all commodities, and a good correlation between tonnage, volume, and value does not currently exist.

Weight factors (W_{Lb} and W_{Tgf}): SLRRs are, by nature, low-MGT freight routes as compared to other railroads. Therefore, the economic consequence of bridge failure felt by the SLRR is dominated by the loss of bridge value/reconstruction cost because it is assumed that freight service can be maintained through alternate modes of transportation; presumably trucks. Since bridge value/reconstruction cost is related to length, W_{Lb} must be greater than W_{Tgf}.

3.2.4 Railroad classification (Rc). Rc, quantifies consequence as an indication of freight transportation efficiency – the higher the efficiency of an SLRR, the greater the consequence of a loss. The maximum operating speed limit, shown in parenthesis in Table IX, is determined by the class of track; therefore, a higher-class track operating

Table VIII.
Recommended weighting factors for *Lb* and *Tgf*

Length function (W_{Lb}) (%)	Gross freight tonnage (W_{Tgf}) (%)	Total (%)
75	25	100

at a higher speed is assumed to more efficiently transport freight. The class of track is defined by the Code of Federal Regulation Title 49-Part 312.9 and the respective assigned values are given in Table IX.

The magnitudes of the values were selected in order to recognize SLRRs that have the ability to operate at higher efficiency while understanding that many SLRRs do not need to operate above Class 1 and, therefore, should not be unduly penalized.

3.2.5 Other issues considered for consequence. Certain additional issues affecting the consequence of failure determination were evaluated for the present study including: bridge distance to connecting route, urban/rural classification, and freight commodity type. Implementation of each of these three features into a prioritization scheme proved to be impractical, however.

3.2.6 Assigned weights for consequence of failure. Assigned weights, or levels of importance, for each consequence parameter discussed are presented in Table X. As with weighting factors for probability of failure, the weighting factors for consequence of failure are, fundamentally, policy decisions. The weighting shown in Table X reflects the results of the literature review (Gralund and Puckett, 1996; Saaty, 1980) and author recommendations.

Railroad class is weighted low because it is not a high priority for typical SLRRs. Human and environmental consequences are also weighted low due to the difficulty in predicting *Hu* and *En*, which has been discussed previously. Overall, the greatest consequence of bridge failure is largely economic and therefore, W_{Ec} is weighted considerably higher than other factors.

Bridge risk values, or relative consequence of failure as defined here, are computed on a relative basis using a weighted calculation of the assigned values between 0 and 100 percent.

4. Application of methodology

Application of the proposed risk-based ranking methodology is summarized in Tables XI and XII for an actual bridge taken from the Pennsylvania SLRR bridge database.

Finally, the relative risk score is calculated based on risk equals probability times consequence from Equation (1):

$$\text{Risk} = \text{Probability} \times \text{Consequence} = 0.46 \times 0.24 = 0.11$$

The risk for each bridge is calculated in turn and then sorted from high to low to establish the structures of highest priority.

	Description		
	Class 3 track (40 mph)	Class 2 track (25 mph)	Class 1 track (10 mph)
Assigned value	1.2	1.1	1.0

Table IX. Assigned values for railroad classification (*Rc*)

Human (W_{Hu}) (%)	Environmental (W_{En}) (%)	Economic (W_{Ec}) (%)	Railroad class (W_{Rc}) (%)	Total (%)
15	15	60	10	100

Table X. Recommended weighting factors for consequence parameters

Table XI.
Summary of example application of methodology for probability of failure

Probability of failure parameter	Value	Comment
R	0.32	Equation (7)
C/L	1.28	Based on engineering evaluation
Sp	6	Very moderate deterioration
A	95	Construction date 1915
Sb	3	Good, minor deterioration
Sc	3	Scour not observed, small stream
F	3.8	Category D for riveted flexural member; Equation (8)
Probability of failure	0.46	Equation (6): $= 1 - \left[\frac{0.45\times0.32}{1} + \frac{0.30\times3}{4} + \frac{0.20\times3}{4} + \frac{0.05\times3.8}{10}\right]$

Table XII.
Summary of example application of methodology for probability of consequence

Probability of consequence parameter	Value	Comment
Hu	1	Other
En	3	Run
Ec	0.14	Equation (10)
Lb	29	Equation (11) for $L_T = 29.0\,\mathrm{ft}$, $n_s = 1$
Tgf	2	MGT = 2
Rc	1.1	Class 2 track
Probability of consequence	0.24	Equation (9): $= \frac{0.15\times1}{10} + \frac{0.15\times3}{10} + \frac{0.60\times0.14}{1} + \frac{0.10\times1.1}{1.2}$

5. Summary and conclusions

The primary objectives of this study were to examine the state-of-the-art for railroad bridge population management and resource allocation decisions and to develop a rational methodology to rank Pennsylvania SLRR bridges in order to best allocate resources for maintenance, rehabilitation, and replacement. Such a methodology does not currently exist in the literature and is of significant interest to SLRR owners and operators in addition to state transportation agencies.

The original study (Laman and Guyer, 2010) conducted a statewide survey to develop a bridge population database. Pennsylvania SLRR bridge inventory and condition assessment data were collected into a database and used as input for the proposed ranking methodology. The bridge population database can also serve as a resource allowing design and construction engineers to review assets that either outperform predictions or consume disproportionate levels of resources for maintenance and operation, allowing for review of design and construction practices providing feedback for future designs decisions. A risk-based, modular framework is proposed where each influence, or parameter, is formulated as a separate, revisable module that can be easily updated or changed. The proposed framework is not intended to act as a stand-alone BMS. Rather, the intent is to provide a decision support system for engineers and managers to use as a tool. Additionally, the modular design facilitates future refinement of the framework if warranted by the improved fidelity of bridge data within the database.

A review was conducted at the beginning of the study to establish the state-of-the-art for a number of issues related to the study, including current thinking with regard to bridge population management, bridge condition assessment and prediction, asset management systems, risk management and prioritization, and sampling procedures. A risk-based prioritization algorithm is proposed to assign a relative risk score to each bridge in the population. The bridges are then ranked according to their score. The risk score is the product of the probability of failure and consequence of failure. Both probability and consequence are quantified by the summation of weighted parameters, which are determined from information within the database. Weight factors consistent with literature were proposed and assigned by the research team for each of the parameters.

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