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Importance Factor for Design of Bridges Against Fire Hazard

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1.0 ABSTRACT

Fire represents a significant hazard to civil infrastructure, including bridges. However, fire hazard is still not accounted for in conventional bridge design. This paper presents an approach for developing an importance factor for overcoming fire hazard in bridges. The importance factor takes into account the degree of vulnerability of a bridge to fire and also the critical nature of a bridge from the point of traffic functionality. The importance factor is derived by assigning weightage factors to key characteristics of bridges, i.e. bridge's geometrical and design features, traffic demand, hazard (risk) likelihood, expected environmental damage, and economic consequences resulting from a fire incident. The proposed importance factor for fire design, which is similar to the one currently used for evaluating wind, and snow loading in buildings, is validated for a number of bridges where fire incidents occurred previously. It is shown through this validation that the proposed method for importance factor can be used as a practical tool for identifying critical bridges from the point of fire hazard and also for developing relevant design strategies for mitigating fire hazard in bridges.

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Keywords: Fire hazard, Importance factor, Bridges, Fire protection, Bridge collapse.

2.0 INTRODUCTION

Bridges are built to last for several decades and serve a variety of commuters. Hence, they are exposed to multiple loadings and various risks throughout their service life. In recent years, bridge fires are becoming a growing concern due to rapid development of urban ground transportation and increased shipping of hazardous materials (flammable materials, spontaneously combustible materials, dangerous materials, etc.) [1, 2]. Further, bridges are open to general population and easily accessible; with minimum or no security at all, hence they are susceptible to vandalism or sabotage which can often lead to fires. Since fire is a destructive force in nature, fires can threaten structural integrity of a bridge and cause significant interruptions to traffic flow.

There have been numerous fire incidents in bridges and this have been documented in the literature [2-7]. Majority of these bridge fires are caused by collision of vehicles, i.e. fuel tankers, freight trucks and multiple car collisions either with vehicles or bridge components [2-6], hence fires in bridges can be explosive in nature. This has been attributed to the fact that collisions occur at high speeds leading to burning of gasoline based fuels, which have relatively low flash points, in an open environment. Thus, bridge fires can reach extremely high temperatures (in the range of 800-900˚C) within the first few minutes of fire initiation and rising to 1000˚C or more in the first thirty minutes [9-11]. The rapid rise of temperature can create high thermal gradients in the structural members which in turn could produce fire induced spalling in concrete or local buckling in steel members [12].

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In many cases, fires in bridges burn-out quickly or are extinguished through firefighting. However in some scenarios, fires can induce significant degradation of capacity of structural members, due to loss of strength and stiffness properties of constituent materials, which often lead to partial or full collapse of bridges [3-6]. Even in the case of minor fire incidents, where no collapse occurs, proper investigation, inspection and maintenance, in the aftermath of a fire incident, is required before the bridge is opened to traffic. Shutting down a bridge for maintenance would require traffic detouring to nearby routes which can impose significant traffic delays in the affected region. Eventually, this would stress the flow of traffic and affect the commuters' pattern in the surrounding highway networks [2, 8].

Fire hazard in bridges can be overcome to a certain extent through provisions of appropriate fire resistance to structural members, such as girders, piers, etc. [2]. Fire resistance is defined as the time duration at which a structural member exhibits adequate performance in terms of integrity, stability and temperature transmission to the unexposed side. In general, fire resistance is achieved via proper design, selection of materials and detailing of the structural members. Unfortunately, at present, there are no specific requirements in codes and standards for fire resistance of structural members in bridges. This is based on the rationale that bridges are open structures and fire safety measures are not needed in the event of fire. Although fire resistance provisions are provided in buildings, the same provisions may not be applicable for bridges due to large differences in key factors such as fire severity, member characteristics and design objectives [2].

The impact of fire on a bridge can be devastating on the traffic flow of that particular region, especially if it results in significant damage to structural members. In order to overcome such devastating impact, appropriate strategies are to be developed to mitigate fire hazard in

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bridges. However, it may not be economical or practical to design all bridges for fire hazard. Therefore, an important factor is required for classifying bridges based on fire risk. The introduction of such an importance factor would greatly enhance the state of design and maintenance of bridges. Such an importance factor for fire design of bridges can be developed on the same lines as that of importance factor used in the design for wind, snow, and earthquake events (loading). However, unlike the aforementioned events, statistical data on fires in bridges are not widely available [2, 7, 13]. Moreover, the associated frequency and sophistication nature of fires add further challenges and complexities. Hence, qualitative assessment based on rational engineering judgment seems to be the method of choice when assessing the state of bridges against fire hazard.

This paper presents the development of an importance factor for fire design of bridges. The proposed method for evaluating importance factor takes into account the vulnerability of bridges to fire and also critical nature of the bridge from the point of traffic functionality.

3.0 FIRE HAZARD IN BRIDGES

In the last two decades, there has been an increase of fire related accidents in bridges, and some of these fire incidents lead to destructive damage. A survey by Battelle [14] reveals that the average number of annual highway vehicle fire incidents was 376,000, which caused 570 civilian deaths and $1.28 billion of property losses.

A fire occurring in the vicinity of a bridge can spread to the bridge structure if there is significant fuel. While the perception may be that it is very unlikely that a bridge can collapse under fire, a recent US-wide survey by the New York state department of transportation has shown that nearly three times more bridges have collapsed, in 1990-2005 period, due to fire than earthquakes [15]. Kodur et al. [16] further reviewed recent bridge fire incidents and clearly illustrated that in some cases, bridge fires can produce significant damage or collapse of structural members leading to major traffic delays, detours and costly repairs. The following fire incidents illustrate the magnitude of fire problem in bridges.

3.1 Recent fire incidents

On April 29, 2007 a major fire broke out at the two span bridge of the I-580 freeway at MacArthur Maze interchange in Oakland, CA, when a fuel tanker transporting 32,500 litters of fuel overturned under the bridge. The burning of highly combustible fuel lead to intense heat producing temperatures in the range of 1100˚C. The strength and stiffness of steel girders, which had no fire proofing, deteriorated due to rapid rise in steel temperatures leading to large deflections in the girders. This resulted in significant fire induced forces in girders and overstressing of connections. As a result, the connections weakened and steel girders collapsed in about 22 minutes. The losses due to fire induced collapse were estimated at $9 million. Further, it took weeks to repair the fire damaged bridge resulting in significant traffic detours [16].

Another major bridge fire occurred on July 28, 2006 at the Bill Williams River Bridge, AZ, when a fuel tanker carrying 28,700 liters of diesel overturned near the bridge [17]. The bridge was comprised of fourteen spans, each having a length of 23.2 meters. The super structure was constructed of prestressed concrete girders underneath a cast-in-place concrete slab. The fire lasted for few hours and affected span numbers 8, 9 and 10. The fire also spread to surrounding wildlife area and burned for two weeks. The post-fire bridge inspection showed spalling of the concrete cover across of the prestressed concrete girders. However, this spalling did not lead to any capacity degradation in the bridge girders. Following the inspection, the bridge was declared to be in good

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condition, except the east overhang of spans 8, 9 and 10 which was closed for immediate rehabilitation.

On March 23, 2003 a car crashed into a fuel tanker transporting 50,000 liters of heating oil on the I-95 Howard Avenue Overpass in Bridgeport, CT. The bridge was supported by 30-inch deep steel girders spanning 22 meters. The truck while trying to avoid the car, slipped along the overpass's concrete barrier and hit two light poles. The heating oil spilled over a length of 100 meters and ignited. The fire lasted for two hours and the temperatures reached about 1100˚C. The high intensity of fire initiated significant buckling in steel girders carrying the overpass. This resulted in partial collapse of steel girders causing both northbound and southbound lanes to collapse. Following the fire, traffic in both directions had to be detoured. The refurbishment of this fire damaged bridge costed about $11.2 million [2, 18-20].

4.0 FACTORS INFLUENCING FIRE PERFORMANCE OF BRIDGES

The performance of a bridge under fire is mainly influenced by the degree of vulnerability of structural members to a fire. On the other hand, the impact of fire on a bridge is dependent on the critical nature of the bridge from the point of traffic functionality. Some of the key factors that influence the fire performance of bridges are discussed below.

4.1 Vulnerability of bridges to fire

The key factors that contribute to vulnerability of bridges to fire hazard are geometrical features of structural members, materials used in their construction, loading and support (restraint) conditions of structural members and fire intensity.

4.1.1 Geometrical features

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Geometry and dimensions of structural members can have a significant influence on their structural performance under fire conditions. Consequently, geometrical features of structural members affect the vulnerability of a bridge to fire. In the case of a steel bridge, factors such as, slenderness of structural members or lateral restraint to girders can significantly affect local or torsional buckling of girders under fire conditions. In the case of a concrete bridge, concrete cover thickness to internal steel reinforcement has a direct bearing on the fire response of reinforced concrete structural members.

4.1.2 Materials used in construction

Performance of bridges under fire exposure is highly dependent on the thermo-physical and mechanical properties of constituent materials that form the structural members. All materials experience loss of strength and elastic modulus properties at high temperatures, but the rate of loss of these properties vary for different materials. For instance, loss of strength and stiffness properties of concrete with temperature is at a slower pace than that of steel. Hence concrete members generally exhibit higher fire resistance as compared to steel structural members. Strength and stiffness of normal strength concrete (NSC) starts to degrade beyond 400˚C, while mechanical properties of steel starts to degrade around 250˚C at significantly higher rate [23-25]. In comparison to concrete and steel, timber is a combustible material and also loses its strength and stiffness at relatively lower temperatures. Thus, the type of material used in the structural members of a bridge has a direct bearing on the vulnerability of that bridge under fire.

4.1.3 Loading and support conditions

The type and intensity of loading, as well as support conditions, can influence the fire performance of structural members. Structural members under static loading and at lower load

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levels achieve higher fire resistance than similar members subjected to dynamic, high load levels. High load levels subject the members to additional stresses, thus the members will have less retention (reserve) capacity under fire. Further, restrained support conditions can significantly enhance fire resistance of flexural members due to the development of fire induced restraint forces that can counter balance the load induced moments. However, in the case of fixed end concrete columns made of high strength concrete, additional forces due to the presence of restraints are generated. Such forces, in some scenarios, could lead to early spalling of concrete cover and initiate premature failure. Thus, the type of support, magnitude and type of loading contributes to the vulnerability of bridges under fire exposure.

4.1.4 Fire intensity

The intensity and duration of fire have a significant bearing on the performance of structural members. Fire intensity and its duration depend on the fuel type and quantity, as well as ventilation characteristics. Building fires tend to burn at lower intensity and progress (grow) at a slower rate than bridge fires due to limited ventilation (oxygen), availability of active and passive protection systems and fuel mainly comprising of cellulose-based materials. On the contrary, bridges are open structures with unlimited oxygen supply. They lack active and passive fire protection measures and the presence of highly flammable hydrocarbon products, can accelerate the rate of growth of fires, producing high intensity fires [4, 5].

4.2 Critical nature of bridges

The second major factor that is to be considered in evaluating the importance of a bridge, from the point of fire hazard, is the critical nature of the bridge. The critical nature of the bridge is influenced by the bridge location and traffic density.

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4.2.1 Bridge location

The importance of a bridge is directly related to its location in the traffic network grid. If the bridge is located in a route connecting natural obstacles (such as valleys or rivers) and if there are no alternative routes for traffic detours, then any closure of that bridge due to fire damage will significantly slow down or shut down the traffic in the region.

4.2.2 Traffic density

Similarly, traffic density can determine the critical nature of the bridge. If a bridge is located on a condense highway or in the surroundings of urban area that serves large number of vehicles daily, loss of operation of such a bridge will cause significant traffic disruptions in the region. This factor is to be considered in evaluating the importance of a bridge.

5.0 APPROACH TO EVALUATE IMPORTANCE FACTOR

Although fire represents a significant hazard to bridges, it is still of a rare occurrence. As a result, it is not economical or practical to design all bridges for fire hazard. Only bridges that are at high risk from the point of fire hazard are to be designed for fire safety. For evaluating fire risk, an importance factor similar to that used for evaluating snow or wind loading in the design of buildings, can be quite useful. The steps associated in the development of importance factor of bridges are explained below.

5.1 Calculation of the importance factor (IF)

The proposed approach for importance factor is developed by taking into account the vulnerability of bridge structural members to fire, as well as the critical nature of the bridge to the traffic flow. The vulnerability of a bridge to fire arises from geometric dimensions and design

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features of its structural members and likelihood of fire occurrence in the vicinity of that bridge. Based on the previous fire incidents in bridges, those aspects were found to be the major contributing factors to the bridge’s state of vulnerability [2, 7, 13].

On the other hand, traffic demand, economic consequences in the aftermath of a fire incident and expected fire losses define the critical nature of a bridge. Bridges with high traffic volumes are more prone to higher losses and traffic disruption due to fire. Further, closure of similar bridges due to inspection or maintenance, in the event of a fire, would require detouring traffic to nearby routes. Such detouring would amplify traffic intensity in the nearby highways and affect the traffic flow in the region.

The key characteristics that define the importance of a bridge; vulnerability to fire and critical nature, are grouped into five classes as shown in Fig.1. Each class is comprised of different parameters that contribute to the importance factor. Within each parameter, there are various sub-parameters that determine the conditions of a specific bridge. The five classes along with their parameters and sub-parameters are tabulated in Table 1.

Based on engineering judgment and recommendations of previous studies [2, 13, 29-30], weightage factors are assigned to different sub-parameters. The weightage factors ($\varphi_{c,p}$), assigned on a scale from 1 to 5, are associated with unique subscripts defining its related class and parameter.

Knowing the maximum weightage factors for various parameters in a bridge, a class factor (ψ_x) is calculated as:

$$\psi_x = \frac{\sum \varphi_{x(\max)}}{\varphi_{total}} \qquad (1)$$

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where,

$\varphi_{x(max)}$ is the maximum weightage factor of each parameter in class (x)

φ_{total} is the summation of maximum weightage factors of all parameters in the fire classes

Then, a class coefficient (Δ_x) can be calculated as the ratio of the summation of the weightage factors of all sub-parameters in class (x) to the summation of the maximum weightage factors of all the parameters in the same class:

$$\Delta_x = \frac{\sum \varphi_{i,x}}{\sum \varphi_{x(\max)}} \tag{2}$$

where,

$\varphi_{i,x}$ is the weightage factor of sub-parameter (i) in class (x)

$\varphi_{x(max)}$ is the maximum weightage factor of each parameter in class (x)

Finally, an overall class coefficient (λ) is evaluated as the summation of the product of class coefficient (Δ_x) and corresponding class factor (ψ_x).

$$\lambda = \sum \Delta_x \psi_x \tag{3}$$

The overall class coefficient *(λ)* is then utilized to assign fire risk grade for a bridge. This is done by comparing the value of the overall class coefficient *(λ)* with numerical scores given in Table 2 and arrive at an importance factor (*IF*). The fire risk associated with bridges is grouped into four grades namely low, medium, high and critical. The risk grades and related overall class coefficient *(λ)* scores are given in Table 2. This importance factor indicates the susceptibility of the bridge to fire hazard. As an example, a bridge with importance factor (*IF*) of 1.5 represents the

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most critical bridge from the point of fire hazard and thus requires some level of fire protection measures to mitigate adverse impact from fire.

The four grades of risk were arrived at based on collected data of fire incidents in previous studies [21, 29-30]. For instance, a survey conducted by the New York State Department of Transportation, revealed that 2.9% of the surveyed bridges collapsed due to fire (52 out of 1746) [21]. Further, Wardhaua and Hadipriono [29] conducted a comprehensive review on 503 bridges and reported that 3.18% of the collapsed bridges were due to fire related causes. Similarly, Scheer [30] showed that 4.9% of bridges collapsed due to fire or explosion (26 out of 536). Hence, in this study, about 5% of the total bridge population is considered to have the highest (critical) risk to fire hazard.

Further, the contribution of each class (influencing factors) to the overall importance factor is illustrated through a pie chart in Fig. 2. Detailed calculations illustrating the application of above procedure to evaluate class factors and importance factor are presented in Appendix A.1 and B.1, respectively.

5.2 Flow chart

Figure 3 illustrates a flow chart in which five steps needed to evaluate importance factor is summarized.

In Step 1, information on various features of the bridge and statistical data related to traffic flow is collected. In Step 2, weightage factors (φ) are assigned to various sub-parameters based on the collected data, recommendations provided herein and engineering judgment. Table 1 provides guidelines for assigning weightage factors to different sub-parameters. Then, individual class coefficients (Δ_x) and overall class coefficient (λ) are evaluated as part of Steps 3 and 4, using Eqs.

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(2) and (3), respectively. Finally, in Step 5, the importance factor (*IF*) is established using the risk grade given in Table 2. A detailed example for the calculation of importance factor is illustrated in Appendix B.1.

5.3 Rationale for assigning weights

As indicated above, a number of factors were taken into consideration in determining the vulnerability and critical nature of bridges. Since each class is comprised of several parameters, the rationale for assigning weightage factors for various sub-parameters under each fire class is discussed herein. In general, the weightage factors are assigned in an ascending numerical order (see Table 1) where the largest value indicates the highest risk (susceptibility) to fire hazard.

5.3.1 Class 1: Geometrical properties and design features (ψ_g)

The geometric properties and design features that contribute to the vulnerability of a bridge arises from the type of structural system, material type, girder span, number of lanes, age, bridge rating and special (service) features. It should be noted that the structural capacity of a given bridge, under fire conditions, is mainly influenced by these geometric features. Hence, the geometric properties and design features were found to be the major contributing class to the fire risk associated with the bridge (ψ_g = 0.44), as illustrated in Fig. 2.

- *Structural system ($\varphi_{g,ss}$)*

Different types of structural systems are used in bridges and the type of structural system has an influence on its vulnerability to fire hazard. Typical structural systems in bridges are grouped under truss/arch, girder-type (simply supported or continuous), cable-stayed and suspension bridges. Cable-stayed and suspension bridges usually have complex load-paths, comprise of larger spans and serve large traffic volumes and these are more susceptible to fire due

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to the use of steel cable components. These bridges were considered to be more vulnerable to fire damage. To reflect the higher risk associated with cable-stayed and suspension bridges, weightage values of 4 and 5 are assigned. For more conventional type of bridges, i.e. girder-type, a weightage factor of 2 or 3 is assigned and a weightage factor of 1 is assigned for truss/arch bridges.

- *Material type* ($\varphi_{g,mt}$)

Bridges are mainly constructed using concrete, steel or timber materials. To reflect the vulnerability of each material type, a weightage factor of 1 to 5 is assigned based on the findings of Wardhaua and Hadipriono [29].

Steel structural members in bridges are more susceptible to fire damage and thus steel bridges are assigned a weightage factor of 5 [2, 29]. Similar to steel bridges, timber bridges are also given a weightage factor of 5 since timber is a combustible material and has poor performance when exposed to elevated temperatures. Concrete bridges can be further grouped under four different types, such as conventional reinforced concrete (RC), pre-stressed concrete (PC), steel-concrete composite construction, and fibre-reinforced polymers (FRP) strengthened concrete. Bridges retrofitted with FRP systems are assigned a weightage factor of 4 because FRP materials decompose at elevated temperatures and lose its strength and stiffness properties at a much faster rate than concrete and steel. In the case of composite bridges, composite action between concrete and steel enhances the fire performance of such bridges, thus they are assigned a weightage factor of 3. It should be noted that high strength concrete (HSC) loses strength at a higher rate than conventional concrete. Hence, bridges constructed with HSC and conventional concrete are assigned a factor of two and one, respectively.

- *Span length* ($\varphi_{g,sl}$)

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The span length of bridges can vary over a wide range depending on the bridges' different design features, intended use, location and presence of natural barriers. It is assumed that the importance of the bridge has somewhat direct correlation to the span length. In general, large span bridges have high dead to live load ratio and serve higher volumes of traffic, therefore they carry higher load intensities. They are critical since they usually span over natural obstacles such as bodies of water. To reflect this, the span length of bridges is grouped under four sub-parameters; namely, less than 50 m, between 50 and 200 m, between 200 and 500 m and more than 500 m and are given weightage factors ($\varphi_{g,sl}$) ranging from 1 to 4, respectively.

- *Number of lanes* ($\varphi_{g,nl}$)

Number of lanes in a bridge reflects indirectly the load carrying capacity and thus is taken as an influencing parameter under geometric properties and design features. The number of lanes is considered to be a dimensional (geometrical) limitation rather than a traffic related parameter. The number of lanes is grouped under three sub-parameters i.e. two, between two to four and more than four lanes. In general, wider bridges serve more commuters, and since the likelihood of accidents increases with the increased number of users and vehicles, bridges with four or more lanes are assigned a weightage factor of 3. Bridges with two and three lanes are assigned a weightage factor 2, while bridges with one to two lanes are assigned a weightage factor of 1.

- *Age* ($\varphi_{g,a}$)

Bridges are built to last for decades, however, structural members in bridges undergo deterioration in properties due to environmental effects (creep and corrosion), fatigue, adverse weather conditions, etc., thus requiring regular inspection, maintenance and upgrading. Such deterioration can impact fire performance of structural members. As an example, excessive cracking in concrete members that develops overtime can lead to faster temperature rise in case of fire.

To account for this parameter, bridges are grouped under four sub-parameters, i.e. bridges with less than 15 years in service, between 15 and 30 years, between 30 and 50 years and more than 50 years. It was shown in the literature that most of the damaged and collapsed bridges are those of 50 years of service or more [29, 30]. Hence, bridges that have been in service for 50 and more years were considered to be more susceptible to damage in case of a fire incident and are given a weightage factor of 4 to represent their higher vulnerability to fire. On the other hand, relatively newer bridges are assigned weightage factors of 1 to 3.

- *Current standard rating ($\varphi_{g,csr}$)*

The national bridge inventory database uses sufficiency rating system to evaluate adequacy of bridges from a functionality aspect [34]. The sufficiency rating is calculated using compiled data collected over the years of service. Accordingly, bridges are grouped under five sub-parameters whose ratings range from 0 to 100. Therefore, a weightage factor ($\varphi_{g,csr}$) of 1 to 5 is assigned based on these ratings; a weightage factor of 1 is given for bridges with sufficiency rating between 80 and 100 and a weightage factor of 5 for bridges with sufficiency rating less than 20. Similarly, weightage factors of 2, 3 and 4 are assigned to bridges with sufficiency rating of 20-40, 40-60, and 60-80, respectively.

- *Additional service features ($\varphi_{g,asf}$)*

This parameter is used to account for special service features in a bridge, since these features sort of reflect the importance of a bridge. Examples of service features include, pedestrian paths, single or double decking, railroad, multi-level overpasses or if the bridge is constructed over a natural obstacle. The complex nature of bridges constructed across natural barriers (such as over water with passage ways to ships) dictates that such bridges to be of high vulnerability to fire hazard. Hence, they are assigned the highest weightage factor of 5. Bridges that provide access to multi-level overpasses and highways or built above tunnels/pipelines are assigned a weightage factor of 4. On the other hand, bridges that accommodate railroad, double and single decking have a weightage factor of 3, 2 and 1, respectively.

It should be noted that when a bridge provides multiple service features, the numerical value of the highest sub-parameter is used in the calculation of the additional service features weightage factor ($\varphi_{g,asf}$). For example, in the calculation of the importance factor for a bridge constructed with double decking ($\varphi_{g,asf} = 2$) and above a water body ($\varphi_{g,asf} = 5$). The designer should only account for the sub-parameter with the highest weightage factor, thus the weightage factor for the additional service features ($\varphi_{g,asf}$) parameter of this bridge is 5.

5.3.2 Class 2: Hazard (fire) likelihood (ψ_h)

The likelihood of fire occurrence is another key factor that influences the vulnerability of bridges. Fires can occur as a result of accidental or manmade incidents. The hazard likelihood is mainly influenced by four parameters identified as; response time, historical/architectural significance, threat perception and possible fire scenario. The hazard likelihood class weightage factor (ψ_h) is evaluated based on weightage factors of these four parameters. Accordingly, this class contributes up to 23% of the importance factor *(IF)*, as shown in Fig. 2.

- *Response time ($\varphi_{h,rt}$)*

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The response time is the expected duration for the first responders to reach the bridge in the event of fire [35]. Determining a response time can be tedious because of the complex nature of its components i.e. time needed to ignition, incident discovery, call processing, dispatch time, first responders' driving time and traffic conditions. Generally, the response time can indirectly be linked to the bridge location from the nearest fire department.

In addition, response time is significantly influenced by the size of the fire, and traffic state at the time of incident. For the sack of simplicity, the response time is grouped into five sub-parameters. The five sub-parameters are based on the time required for the first responders to reach a bridge in case of a fire incident. The five sub-parameters are response time of less than 5 min, between 5 and 10 min, between 10 and 20 min, between 20 and 30 min and more than 30 min. Each sub-parameter is assigned a weightage factor ranging from 1 to 5, respectively. Although the average response time for building fires is between 9-14 min [37], several fire incidents show that the response time for fire incidents of bridges could be as long as 25 min [10, 11]. Designers can estimate the required response time from previous data or in consultation with the local fire departments.

- *Historical/architectural significance ($\varphi_{h,hasi}$)*

It is generally accepted that some bridges carry historical or architectural significance and considered iconic landmarks of a particular city or era. Such bridges represent a small percentage of the overall bridge population. To distinguish between different bridges from the historical/architectural point of view, bridges are grouped into three sub-parameters, namely, conventional, landmark and prestigious bridges. Conventional bridges are common bridges and are assigned a weightage factor of 1. Landmark bridges are symbolic to the region or state and are

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given a weightage factor of 2. On the other hand, prestigious bridges, which are given a weightage factor of 3, are of historical or national significance, architecturally very appealing, associated with patriotic images and have been in operation for a long period of time. This parameter is solely based on qualitative assessment.

- *Threat perception* ($\varphi_{h,tp}$)

History of previous fire incidents in the vicinity of a bridge is another component that can indicate the likelihood of fires near that bridge (ψ_h). Three possibilities are considered, i.e. bridge with no history of previous fire incidents, lack of data on the bridge in question, and bridge with high threat perception. The first two sub-parameters are given weightage factors of 1 and 2, respectively. On the other hand, bridges with high threat perception from vandalism or terrorism are given a weightage factor of 3. Thus, a designer should account for the complex nature of this parameter using previous statistical data and in consultation with the department of transportation authorities.

- *Probable fire scenario* ($\varphi_{h,pfs}$)

As mentioned earlier, fire performance of a structural member is influenced by the intensity and duration of fire. Depending on the state of traffic, fuel availability and incident location, multiple fire scenarios can arise. To represent different possibilities of fire scenarios and based on recent fire incidents [2, 3, 13, 15], five types of fire scenarios (sub-parameters) are considered in evaluating fire-based importance factor. The five possible fire scenarios are listed in Table 1. For example, fires resulting from small vehicle collision above/below a bridge have a weightage factor of 1, while fires initiated by collision of fuel freight ship with a bridge pier has a weightage factor of 5. Other fire scenarios are also possible such as fire due to collision of truck, fuel tanker and multiple vehicles; with structural components of the bridge (i.e. piers, parapets) or with other vehicles, in the vicinity of the bridge.

5.3.3 Class 3: Traffic demand (ψ_t)

Traffic demand is a key factor that governs the importance of a bridge from the point of traffic flow in the region. This item shed light on the traffic capacity of a bridge and its role in the transportation network. Two main parameters are identified, i.e. Average Daily Traffic (ADT) volume and classification of facility location. The traffic demand has a class factor of 11% (ψ_t = 0.11) of the overall importance factor.

- *Average Daily Traffic (ADT) ($\varphi_{t,adt}$)*

The average daily traffic (ADT) is defined as the total daily volume of traffic on a bridge. In other words, it is a measure of how many vehicles a bridge serves daily. Bridges with high ADT rates are considered as important component to the transportation network. Five ADT limits (sub-parameters) were identified herein, i.e. less than 1000 vehicles/day, between 1,000 and 5,000 vehicles/day, between 5,000 and 15,000 vehicles/day, 15,000 and 50,000 vehicles/day and more than 50,000 vehicles/day. For bridges serving less than 1,000 vehicles/day a weightage factor of 1 is assigned, while bridges with higher traffic volume of more than 50,000 vehicles/day are assigned the highest weightage factor of 5.

- *Facility location ($\varphi_{t,fl}$)*

Bridges can be located in rural, sub-urban and urban areas within a transportation grid. Hence, three sub-parameters are used to represent the location of a bridge. Bridges located in rural counties tend to have shorter spans and fewer number of lanes because they serve remote places with low traffic rates. However, bridges in sub-urban sites have relatively larger spans and serve

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more traffic than those located at rural sites. Urban bridges are considered to be most important bridges of all, since they provide main routes to metropolitan areas and serve larger volumes of traffic. Based on the location of a bridge, rural, sub-urban and urban bridges have a weightage factor of 1, 2 and 3, respectively.

- *5.3.4 Class 4: Economic consequences (ψ_e)*

In the aftermath of a fire incident, both structural integrity of the bridge and efficiency of traffic network are jeopardized. Hence, the efficiency of traffic flow in the region can be adversely affected. For example, after a fire incident, the damaged bridge needs to be shut down for inspection and necessary repairs. This would require detouring of traffic to nearby roads. Detouring traffic leads to additional delays in travel time and merchandise delivery that can impact businesses operations. On the contrary, economic consequences can be minimal in the case of a fire incident on bridges located in remote areas, serve insignificant volume of traffic or have multiple alternative routes.

This class has a class factor (ψ_e) of 13% from the overall predicted importance factor. To reflect this, three parameters, namely presence of alternative routes, expected time, and cost of restoration and repair are identified.

- *Alternative routes ($\varphi_{e,ar}$)*

Presence of alternate routes provide commuters with substitute roads, therefore minimizing any possible delays and interruptions in case of shut down of a bridge for maintenance or repair after a fire incident. To reflect this, three sub-parameters are identified based on the availability of alternate routes to the bridge in question. For bridges with nearby alternative routes (less than 10 km), a weightage factor ($\varphi_{e,ar}$) of 1 is assigned. Bridges with alternative routes in the range of 10-

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20 km are given a weightage factor of 2, while for bridges with alternative route of beyond 20 km a weightage factor of 3 is assigned. In order to assign a weightage factor to this parameter, designers need to collect relative information from the available maps and department of transportations.

- *Time expected for repair ($\varphi_{e,ter}$)*

After a fire incident, the bridge is to be shut down for post-fire inspection and possible repair. Unexpected detouring of traffic due to repair as a result of fire damage can adversely affect the traffic flow in the affected region. The time expected to repair is a function of extent of fire damage and is reflected through three sub-parameters. The sub-parameters are minor, major and longer interruption to traffic flow when the time to repair the bridge is three months or less ($\varphi_{e,ter}$ = 1), from three to nine months ($\varphi_{e,ter}$ = 2) and more than nine months ($\varphi_{e,ter}$ = 3), respectively.

- *Cost expected for repair ($\varphi_{e,cer}$)*

Similar to time expected for repair, the cost of repairing a damaged bridge is also considered as another parameter under economic consequences class. Previous fire incidents have shown that in cases of partial or complete collapse of a bridge, significant downtime and resources are needed to restore the bridge to functionality. To reflect this parameter, three sub-parameters are considered, namely minor, major and substantial repair and this is based on the expected cost to repair a damaged bridge. If the total cost for repair is to be less than one million, from one to three million and more than three million dollars, weightage factors of ($\varphi_{e,cer}$) = 1, 2 and 3 are

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assigned, respectively. It should be noted that additional costs arising from firefighting, cleaning incident site from debris, merchandise delays, etc. might have to be considered as well.

5.3.5 Class 5: Expected fire losses (ψ_f)

In case of a fire incident, not only life and property losses, but also substantial environmental damage can occur. It should be noted that data on life/property losses as well as environmental damage statistics are not available yet. Hence, qualitative assessment and engineering judgment can be of aid herein. It should be noted that this class contributes 9% of the overall importance factor.

- *Life/property losses ($\varphi_{f,lp}$)*

The number of casualties/injuries is highly dependent on the number of persons present at the time of incident. In addition to drivers and passengers, casualties arising from first responders should also be taken into account. Although loss of life is usually minimal, in bridge fires, property losses can be significant.

Life/property losses can be grouped under three sub-parameters, i.e. minimum to no injuries, minimum casualties and many casualties. Minimum to no injuries can result in incidents where small fires occur due to car crashes, without any life loss, and is assigned a weightage factor ($\varphi_{f,lp}$) of 1. Minimum casualties can be considered if victims are basically drivers involved in the collision or accident and hence is assigned a weightage factor of 2. However, fatal casualties represent injuries and life losses of drivers, passengers, public and first responders. Fatal injuries are expected in case of larger fires, partial or major collapse of a bridge, hence they are assigned the highest weightage factor of 3. Although, in some cases general public could be able to move

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away and evacuate from the fire scene, if fire incidents occur on bridges on natural obstacles where there are no exit paths, significant life/property losses can occur.

- *Environmental damage ($\varphi_{f,end}$)*

Collateral environmental damage is often expected as part of major fire incidents. Such losses can be as minor as damage to aesthetical appearance ($\varphi_{f,end} = 1$) or significant as in starting of fires in surrounding areas (affecting wild life). Unacceptable environmental damage can be extended to include damage to wild life, air pollution, water pollution in cases of oil spill resulting from overturning of railroad tanker turnover or fuel tanker colliding a bridge's pier and is assigned a weightage factor of 3. For cases of significant damage or minor damage, a weightage factor of 2 and 1 is assigned.

5.4 Validation of the proposed approach

The above approach was validated by evaluating the importance factor for seven bridges that experienced fire incidents. These fire incidents occurred at I-75 Overpass near Hazel Park, MI; Stop Thirty Road, State Route 386 Nashville, TN; Puyallup River Bridge, WA; I-80/880 interchange near Oakland, CA; I-95 Howard Avenue Overpass in Bridgeport, CT; I-20/I-59/I-65 interchange in Birmingham, AL; and Norwalk River Bridge near Ridgefield, CT. Three of these were concrete bridges, while the remaining four were steel bridges. Further details on the selected fire incidents are presented in Table 3, as well as Tables B.1-B.3 in the Appendix.

5.4.1 I-75 Overpass near Hazel Park, MI, fire incident

On July 15, 2009 a major fire broke out after a fuel tanker carrying highly flammable fuel crashed into another truck under the 9-mile road overpass at the I-75 expressway near Hazel Park, MI. The incident occurred when a car driver lost control along the overpass of I-75 and caused the

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following fuel tanker to crash. This resulted in a high intensity fire on the bridge resulting from the burning of 50,000 liters of fuel being transported in the fuel tanker. The fire temperatures were in the range of 1100˚C. The unprotected overpass steel girders weakened due to high temperatures in steel and finally collapsed in about 22 minutes. The collapse of the overpass caused significant losses and major traffic delays [2, 18-19].

To assess the applicability of the proposed approach, the importance factor was evaluated for this bridge. The various characteristics (sub-parameters) of this bridge were compiled from literature [2, 18-19] and the corresponding weightage factors are assigned as summarized in Table B.1. Sample calculations involved in evaluating the importance factor are also illustrated in Appendix B.1. The overall class coefficient *(λ)* for this bridge works out to be 0.66 indicating that the bridge comes under "high" risk category. Thus, the importance factor for this bridge is 1.2. The unprotected steel girders in this bridge lasted for 25 minutes. Hypothetically, the bridge could have survived if the steel girders were protected with fire insulation.

5.4.2 Stop Thirty Road, State Route 386 Nashville, TN, fire incident

On June 20, 2007 a rear-end collision occurred between a fuel tanker and a loaded dump truck on State Route 386 under the Stop Thirty Road Bridge, TN. The bridge, constructed in 1981, has two lanes that have a span of 70.6 meters. The bridge is constructed of pre-stressed concrete hollow box-beams. The design strength of concrete used in the girders is 20 MPa and the internal reinforcement consisted of epoxy-coated steel (pre-stressed) reinforcement. According to Shutt [10], the affected span in the fire was 36.5 meters. Post-fire inspection of the bridge indicated that minor spalling of concrete occurred, but there was no structural damage. Following the fire, the bridge was reopened for traffic after inspection [10].

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Table B.2 summarizes collected data on various sub-parameters and assigned weightage factors. The computed overall class coefficient *(λ)* for this bridge works out to be 0.50 indicating that the bridge falls under "medium" risk category. Since, minor damage has been reported and no disruption of traffic occurred, this bridge did not need to be designed for fire. This infers that the prediction (importance factor) from the proposed method is in agreement with the observations (no significant damage) documented in the fire incident.

5.4.3 Puyallup River Bridge, WA, fire incident

On the afternoon of December 11, 2002, a railroad tanker collided under the Puyallup River Bridge, WA. The tanker was carrying 450,000 liters of methanol fuel at the time of collision. The fire was of explosive nature and temperatures reached more than 1000˚C in the first 30 minutes [11]. The burning lasted for about one hour. The precast concrete bridge had a span of 44.5 meters. The concrete used for the girders had a design compressive strength of 48 MPa. The bridge was closed for a day after the fire incident. Upon post-fire inspection, no major damage has been reported and the bridge was opened to traffic on the following day [11].

As shown in Table B.3, the computed overall class coefficient *(λ)* for this bridge is 0.47, thus the bridge falls under "medium" risk category. Again, good agreement in the computed importance factor can be seen between the proposed method and actual observations in the fire incident.

As part of this validation, the above procedure was applied to four other bridges that experienced fire incidents; namely, the I-80/880 interchange in Oakland, CA; I-95 Howard Avenue Overpass in Bridgeport, CT; I-20/I-59/I-65 interchange in Birmingham, AL; and Bridge over the Norwalk River near Ridgefield, CT. The results of the analysis are tabulated in Table 3. The predicted importance factors are in close agreement with the perceived risk in actual fire incidents. Hence, the proposed method is deemed to be acceptable for evaluating the importance factors for fire design of bridges.

5.5 Case Studies

To further illustrate the applicability of the proposed importance factor for fire design of bridges, two hypothetical case studies are presented. The two cases selected for evaluating importance factor for fire design are; a typical cable-stayed bridge, and a suspension bridge. These two cases represent bridges which fall under high and critical risk categories.

5.5.1 Case Study 1: Cable-stayed bridge

A typical pre-stressed concrete cable-stayed bridge has been constructed 30 years ago. This single deck bridge is considered as one of the major landmarks of the city. It has a span of 250 meters and carries six lanes of traffic. The bridge serves an average traffic of 67,000 vehicles per day and is located in a metropolitan area, but the nearest major alternate route is within 5-10 km.

According to the national inventory system, the bridge has a current rating of 38. Historical data indicate that the bridge has experienced few accidents that led to small fires near the vicinity of the bridge. In previous fire incidents, the shortest response time from fire department was 13 minutes. The bridge needs to be retrofitted to account for a possible fire incident resulting from multiple car collisions with a large fuel tanker. Such event could cause huge fire losses and significant environmental pollution. Further, any major fire on the bridge is expected to close it down for weeks. The overall anticipated cost in case of a bridge is shut down is about 1-2 million dollars.

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Based on the above information, weightage factors were assigned to various sub-parameters and an importance factor was evaluated for the bridge. The characteristics and weightage factors are summarized in Table B.4. Applying the proposed approach, the importance factor was found to be 1.2, indicating that the bridge to be under high risk category for fire hazard.

5.5.2 Case Study 2: Suspension bridge

A steel suspension bridge with a span of 1,200 meters, carrying eight lanes above water, was constructed 53 years ago. The bridge serves 110,000 vehicles per day. The bridge is considered to be one of the city's prestigious landscapes and is the only major route to travel across the river banks. The average response time from the closest fire department to the bridge site is 11 minutes. Due to heavy traffic and deteriorated state of the bridge, the previous maintenance inspection showed that it has a rating of 30. The state of the bridge needs to be enhanced to withstand a possible fire due to fuel freight ship collision with a bridge pier. The collision is expected to severely damage bridge's substructure causing partial collapse, large number of casualties and unacceptable environmental pollution due to fuel spill. Expected time and cost to rebuild the facility is 1 year and more than 2 million dollars, respectively.

The above approach is utilized to evaluate the importance factor assuming large fire losses and significant environmental damage. Table B.5 summaries the calculation of the importance factor. Using Table 2, the risk grade for fire hazard is determined to be "critical" and the importance factor to be 1.5. Since the bridge falls under "critical" risk category, fire proofing of steel structural members would enhance the fire performance of the bridge.

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6.0 FIRE MITIGATION STRATIGIES

The proposed approach for importance factor can be applied for evaluating fire risk associated with bridges at the early stage of design or prior to rehabilitation of an existing bridge. The rehabilitation could be due to scheduled maintenance, upgrading, improving the bridge's state to meet current code provisions, or retrofitting after an incident.

The vulnerability of a bridge to fire can be assessed using the proposed importance factor. If the bridge is found to be in "critical" or "high" risk category, the vulnerability of the bridge to fire hazard can be minimized by providing fire protection to structural members. Hence, bridges with high vulnerability to fire and of importance to the transportation network can be provided with fire ratings of one to two hours. In the case of concrete bridges, 1 to 2 hour of fire rating to structural members can be achieved through the provision of sufficient concrete cover thickness. Hence, no external fire protection may be needed for conventional concrete members. However, in the case of steel and timber bridges, external fire proofing to structural members may be needed to achieve desired fire ratings. On the other hand, composite bridges can achieve adequate fire resistance through the utilization of composite action and also proper application of concrete cover to members.

7.0 CONCLUSIONS

Based on the information presented in the paper, the following conclusions can be drawn.

- Fire represents a severe hazard in bridges and can lead to significant damage or collapse of structural members. The adverse effects of fire on a bridge can be mitigated by providing appropriate fire resistance to structural members.

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- A methodology for evaluating importance factor for fire design of bridges is presented. The approach takes into account the level of vulnerability and critical nature of the bridge from the point of traffic functionality in evaluating the importance factor.
- The proposed importance factor is similar to the one used for evaluating wind and snow loading in buildings and can be applied in the design of new bridges or in retrofitting of existing bridges. Thus, the importance factor can be used as a benchmark to assess relative fire risk in bridges and also develop appropriate strategies for mitigating fire hazard in bridges.
- The fire risk in a bridge can be grouped into four grades ranging from critical to low. About 5% of bridges fall under "critical" risk category and appropriate fire protection to structural members in "critical" bridges can minimize the adverse effects of fire hazard to a great extent.
- It should be noted that the proposed importance factor is derived by considering a wide range of parameters to take into account various bridge characteristics and importance of the bridge. Many of these parameters are based on both engineering judgment and statistical data from previous bridge fire incidents. However, if better data on parameters is available for a bridge then the importance factor for that bridge can be evaluated based on actual data of that specific bridge.

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9.0 NOMENCLATURE

φ	Parameter weight
ψ	Class factor
$\varphi_{x(max)}$	Maximum weightages factors of each parameter in class (*x*)
$\varphi_{i,x}$	Weightage factor of sub-parameter (*i*) in class (*x*)
φ_{total}	Summation of maximum weightages factors of all parameters
Δ	Class coefficient
$\varphi_{i,x}$	Score value in an individual parameter of class (*x*)
λ	Overall class coefficient
IF	Importance Factor

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11.0 APPENDIX

A.1 Calculation of class factor (ψ)

The following steps illustrate the calculation of class factors for different fire classes.

$$\psi_x = \frac{\sum \varphi_{x(\max)}}{\varphi_{total}}$$

where,

$\varphi_{x(max)}$ is the maximum weightage factors of parameters in class (x)

φ_{total} is the summation of maximum weightage factors of all parameters

For Class 1; "geometrical properties and design features", maximum weightage factor is given by,

$$\Sigma \varphi_{g(max)} = 5 + 5 + 4 + 3 + 4 + 5 + 5 = 31$$

Similarly, maximum weightage factor for classes 2, 3, 4, and 5 are:

$$\Sigma \varphi_{h(max)} = 5 + 3 + 3 + 5 = 16$$

$$\Sigma \varphi_{t(max)} = 5 + 3 = 8$$

$$\Sigma \varphi_{e(max)} = 3 + 3 + 3 = 9$$

$$\Sigma \varphi_{f(max)} = 3 + 3 = 6$$

The sum of the maximum weightage factor for all classes is given as:

$$\varphi_{total} = 31 + 16 + 8 + 9 + 6 = 70$$

Then, class factor (ψ_x) for each class is given by:

$$\psi_g = \frac{\sum \varphi_{g(\max)}}{\varphi_{total}} = \frac{31}{70} = 0.44$$

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$$\psi_h = \frac{\sum \varphi_{h(\max)}}{\varphi_{total}} = \frac{16}{70} = 0.23$$

$$\psi_t = \frac{\sum \varphi_{t(\max)}}{\varphi_{total}} = \frac{8}{70} = 0.11$$

$$\psi_f = \frac{\sum \varphi_{f(\max)}}{\varphi_{total}} = \frac{6}{70} = 0.09$$

$$\psi_e = \frac{\sum \varphi_{e(\max)}}{\varphi_{total}} = \frac{9}{70} = 0.13$$

B.1 Example illustrating calculations of importance factor for I-75 Bridge near Hazel Park, MI.

Step 1: Collecting data and statistics (from Refs. 2, 6 and 19)

Step 2: Assigning weights (φ) for different parameters (as in Table B.1)

Step 3: Calculation of individual class coefficients (Δ_x)

Hence, the individual class coefficients (*Δ*) are as follows:

$$\Delta_x = \frac{\sum \varphi_{i,x}}{\sum \varphi_{x(\max)}}$$

where,

$\varphi_{i,x}$ is the weightage factor of sub-parameter (*i*) in class (*x*)

$\varphi_{x(max)}$ is the maximum weightage factors of each parameter in class (*x*)

$$\Delta_g = \frac{2+3+2+3+3+1+4}{5+5+4+3+4+5+5} = \frac{18}{31} = 0.58$$

$$\Delta_h = \frac{3+1+1+4}{5+3+3+5} = \frac{9}{16} = 0.56$$

$$\Delta_t = \frac{3+3}{5+3} = \frac{6}{8} = 0.75$$

$$\Delta_e = \frac{1+3+3}{3+3+3} = \frac{7}{9} = 0.77$$

$$\Delta_f = \frac{3+3}{3+3} = \frac{6}{6} = 1.0$$

Step 4: Calculation of overall class coefficient (λ)

Then, the overall class coefficient (λ) is given by:

$$\lambda = \Delta_g \times \psi_g + \Delta_h \times \psi_h + \Delta_t \times \psi_t + \Delta_e \times \psi_e + \Delta_f \times \psi_f$$

$$\lambda = 0.58 \times 0.44 + 0.56 \times 0.23 + 0.75 \times 0.11 + 0.77 \times 0.13 + 1 \times 0.09 = 0.66$$

Step 5: Obtaining risk grade and Importance factor (IF)

From Table 2, Risk grade for the bridge is "high" and associated importance factor is 1.2.

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Table B.1

Table B.2

Table B.3

Table B.4

Table B.5

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List of Tables:

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Table 1 Weightage factors based on the different features of a bridge

Class I: Geometrical properties and design features (ψ_g = 0.44)			
Parameter	***Sub-parameters***	***Weightage factor ($\varphi_{i,x}$)***	***Max. weightage factor ($\varphi_{i,x(max)}$)***
Structural system	Truss/Arch	1	5
	Girder - continuous	2	
	Girder - simply supported	3	
	Cable-stayed	4	
	Suspension	5	
Material type	Reinforced concrete bridge	1	5
	High strength/(pre-stressed) concrete bridge	2	
	Steel-concrete composite bridge	3	
	Concrete bridge strengthened with external FRP	4	
	Steel and timber bridges	5	
Span (m)	<50	1	4
	50-200	2	
	200-500	3	
	>500	4	
No. of lanes	2	1	3
	2-4	2	
	>4	3	
Age (years)	<15	1	4
	15-29	2	
	30-50	3	
	>50	4	
Current rating	100	1	5
	60-80	2	
	40-60	3	
	20-40	4	
	<20	5	
Additional service features	1 deck	1	5
	2 decks + pedestrians	2	
	Accommodates railroad	3	
	Multi-level	4	

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	Above water	5	
Class II: Hazard (fire) likelihood (ψ_h = 0.23)			
Parameter	***Sub-parameters***	***Weightage factor ($\varphi_{i,x}$)***	***Max. weightage factor ($\varphi_{i,x(max)}$)***
Response time (min)	<5	1	5
	5-10	2	
	10-20	3	
	20-30	4	
	>30	5	
Historical/architectural significance	Conventional	1	3
	Landmark	2	
	Prestigious	3	
Threat perception	None (low)	1	3
	Not available (medium)	2	
	Frequent (high)	3	
Fire scenario	A small vehicle fire above /under the bridge	1	5
	A large truck collision and fire with other vehicles	2	
	A fuel tanker collision and fire with bridge sub-structure	3	
	Major fuel tanker collision and fire with multiple vehicles and against bridge sub-structure	4	
	Fire due to fuel freight ship collision with a bridge pier	5	
Class III: Traffic demand (ψ_t = 0.11)			
Parameter	***Sub-parameters***	***Weightage factor ($\varphi_{i,x}$)***	***Max. weightage factor ($\varphi_{i,x(max)}$)***
ADT (vehicles/day)	<1,000	1	5
	1,000-5,000	2	
	5,000-15,000	3	
	15,000-50,000	4	
	>50,000	5	
Facility location	Rural	1	3
	Sub-urban	2	
	Urban	3	
Class IV: Economic impact (ψ_e = 0.13)			

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Parameter	***Sub-parameters***	***Weightage factor ($\varphi_{i,x}$)***	***Max. weightage factor ($\varphi_{i,x(max)}$)***
Closeness to alt. routes (km)	<10	1	3
	10-20	2	
	>20	3	
Time expected for repair (month)	<3	1	3
	3-9	2	
	>9	3	
Cost expected for repair	< 1 million	1	3
	1-3 million	2	
	>3 million	3	
Class V: Expected fire losses (ψ_f = 0.09)			
Parameter	***Sub-parameters***	***Weightage factor ($\varphi_{i,x}$)***	***Max. weightage factor ($\varphi_{i,x(max)}$)***
Life/property losses	Minimum to no injuries	1	3
	Minimum casualties	2	
	Many casualties	3	
Env. damage	Minor damage	1	3
	Significant damage	2	
	Unacceptable damage	3	

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Table 2 Risk grades and associated importance factors for fire design of bridges

Risk grade	**Overall class coefficient (λ)**	**Importance factor (*IF*)**
Critical	≥0.95	1.5
High	0.51-0.94	1.2
Medium	0.20-0.50	1.0
Low	<0.20	0.8

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Table 3 Validation of the proposed approach for evaluating importance factor for fire design

Case no.	**Bridge fire incident**	**Date**	**Observation from post fire inspection**	**Predicted fire risk**		
				λ	**Risk grade**	***IF***
1	I-75 Overpass near Hazel Park, MI.	July 15, 2009	Complete collapse of steel girders within 20 minutes into the fire.	0.66	High	1.2
2	Stop Thirty Road, State Route 386 Nashville, TN.	June 20, 2007	Minor fire damage to structural members, but no disruption to traffic since the bridge was reopened to traffic immediately.	0.50	Medium	1.0
3	Puyallup River Bridge, WA.	December 11, 2002	No major fire damage and the bridge was open for traffic on the following day.	0.47	Medium	1.0
4	I-80/880 interchange in Oakland, CA.	April 29, 2007	Upper connector ramp steel girders collapsed after 23 minutes into fire [31].	0.67	High	1.2
5	I-95 Howard Avenue Overpass in Bridgeport, CT.	March 26, 2003	Collapse of southbound lanes and partial collapse of northbound lanes after two hours of fire exposure.	0.64	High	1.2
6	I-20/I-59/I-65 interchange in Birmingham, AL.	January 5, 2002	The girders of the main span sagged off about 3 meters [32].	0.69	High	1.2

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7	Bridge over the Norwalk River near Ridgefield, CT.	July 12, 2005	Four fire affected beams were tested by the FHWA and indicated no deterioration [33].	0.47	Medium	1.0

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Table B.1 Detailed example (I-75 bridge near Hazel Park, MI.)

Class I: Geometrical properties and design features (ψ_g = 0.44)			
Parameter	**Sub-parameters**	φ_g	$\varphi_{g(max)}$
Structural system	Continuous	2	5
Material type	Steel-concrete composite bridge	3	5
Span (m)	50-200	2	4
No. of lanes	>4	3	3
Age (years)	30-50	3	4
Current rating	100	1	5
Additional service features	Multi-level	4	5
	Σ	**18**	**31**
Class II: Hazard likelihood (ψ_h = 0.23)			
Parameter	**Sub-parameters**	φ_h	$\varphi_{h(max)}$
Response time (min)	10-20	3	5
Historical significance	Conventional	1	3
History of fires	None	1	3
Fire scenario	Major fuel tanker collision	4	5
	Σ	**9**	**16**
Class III: Traffic demand (ψ_t = 0.11)			
Parameter	**Sub-parameters**	φ_t	$\Phi_{t(max)}$
ADT	5,000-15,000	3	5
Facility location	Urban	3	3
	Σ	**6**	**8**
Class IV: Economic impact (ψ_e = 0.13)			
Parameter	**Sub-parameters**	φ_e	$\varphi_{e(max)}$
Alt. routes	<10 km	1	3
Time expected for repair	>9 months	3	3
Cost expected for repair	>3 million	3	3
	Σ	**7**	**9**
Class V: Expected fire losses (ψ_f = 0.09)			
Parameter	**Sub-parameters**	φ_f	$\varphi_{f(max)}$
Life/property losses	Many casualties	3	3
Env. damage	Unacceptable damage	3	3
	Σ	**6**	**6**

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Table B.2 Characteristics of Stop thirty Road, State Route 386, Nashville, TN and associated weightage factors

Class I: Geometrical properties and design features (ψ_g = 0.44)			
Parameter	***Sub-parameters***	φ_g	$\varphi_{g(max)}$
Structural system	Continuous	2	5
Material type	High strength/(pre-stressed) concrete bridge	2	5
Span (m)	50-200	2	4
No. of lanes	2	1	3
Age (years)	15-30	2	4
Current rating	20-40	4	5
Additional service features	Multi-level	4	5
	Σ	**17**	**31**
Class II: Hazard likelihood (ψ_h = 0.23)			
Parameter	***Sub-parameters***	φ_h	$\varphi_{h(max)}$
Response time (min)	10-20	3	5
Historical significance	Conventional	1	3
History of fires	None	1	3
Fire scenario	Major fuel tanker collision	4	5
	Σ	**9**	**16**
Class III: Traffic demand (ψ_t = 0.11)			
Parameter	***Sub-parameters***	φ_t	$\Phi_{t(max)}$
ADT	1,000-5,000	2	5
Facility location	Sub-urban	2	3
	Σ	**4**	**8**
Class IV: Economic impact (ψ_e = 0.13)			
Parameter	***Sub-parameters***	φ_e	$\varphi_{e(max)}$
Alt. routes	<10 km	1	3
Time expected for repair	<3 months	1	3
Cost expected for repair	<1 million	1	3
	Σ	**3**	**9**
Class V: Expected fire losses (ψ_f = 0.09)			
Parameter	***Sub-parameters***	φ_f	$\varphi_{f(max)}$
Life/property losses	Minimum to no injuries	1	3
Env. damage	Minor damage	1	3
	Σ	**2**	**6**

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Table B.3 Characteristics of Puyallup River Bridge, WA and associated weightage factors

Class I: Geometrical properties and design features (ψ_g = 0.44)			
Parameter	**Sub-parameters**	φ_g	$\varphi_{g(max)}$
Structural system	Continuous	2	5
Material type	High strength/(pre-stressed) concrete bridge	2	5
Span (m)	<50	1	4
No. of lanes	2-4	1	3
Age (years)	<15	1	4
Current rating	100	1	5
Additional service features	Multi-level	4	5
	Σ	**12**	**31**
Class II: Hazard likelihood (ψ_h = 0.23)			
Parameter	**Sub-parameters**	φ_h	$\varphi_{h(max)}$
Response time (min)	10-20	3	5
Historical significance	Conventional	1	3
History of fires	None	1	3
Fire scenario	Major fuel tanker collision	4	5
	Σ	**9**	**16**
Class III: Traffic demand (ψ_t = 0.11)			
Parameter	**Sub-parameters**	φ_t	$\Phi_{t(max)}$
ADT	1,000-5,000	2	5
Facility location	Sub-urban	2	3
	Σ	**4**	**8**
Class IV: Economic impact (ψ_e = 0.13)			
Parameter	**Sub-parameters**	φ_e	$\varphi_{e(max)}$
Alt. routes	>30 km	3	3
Time expected for repair	<3 months	1	3
Cost expected for repair	<1 million	1	3
	Σ	**5**	**9**
Class V: Expected fire losses (ψ_f = 0.09)			
Parameter	**Sub-parameters**	φ_f	$\varphi_{f(max)}$
Life/property losses	Minimum to no injuries	1	3
Env. damage	Minor damage	1	3
	Σ	**2**	**6**

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Table B.4 Characteristics of typical cable-stayed bridge and associated weightage factors

Class I: Geometrical properties and design features (ψ_g = 0.44)			
Parameter	**Sub-parameters**	φ_g	$\varphi_{g(max)}$
Structural system	Cable-stayed	4	5
Material type	High strength/(pre-stressed) concrete bridge	2	5
Span (m)	200-500	3	4
No. of lanes	>4	3	3
Age (years)	30-50	3	4
Current rating	20-40	4	5
Additional service features	1 deck	1	5
	Σ	**20**	**31**
Class II: Hazard likelihood (ψ_h = 0.23)			
Parameter	**Sub-parameters**	φ_h	$\varphi_{h(max)}$
Response time (min)	10-20 min	3	5
Historical significance	Landmark	2	3
History of fires	Frequent	3	3
Fire scenario	Major fuel tanker collision	4	5
	Σ	**12**	**16**
Class III: Traffic demand (ψ_t = 0.11)			
Parameter	**Sub-parameters**	φ_t	$\Phi_{t(max)}$
ADT	>50,000	5	5
Facility location	Urban	3	3
	Σ	**8**	**8**
Class IV: Economic impact (ψ_e = 0.13)			
Parameter	**Sub-parameters**	φ_e	$\varphi_{e(max)}$
Alt. routes	<10 km	1	3
Time expected for repair	3-9 months	2	3
Cost expected for repair	1-3 million	2	3
	Σ	**5**	**9**
Class V: Expected fire losses (ψ_f = 0.09)			
Parameter	**Sub-parameters**	φ_f	$\varphi_{f(max)}$
Life/property Losses	Many casualties	3	3
Env. damage	Significant damage	2	3
	Σ	**5**	**6**

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Table B.5 Characteristics of major suspension bridge and associated weightage factors

Class I: Geometrical properties and design features (ψ_g = 0.44)			
Parameter	**Sub-parameters**	φ_g	$\varphi_{g(max)}$
Structural system	Suspension	5	5
Material type	Steel	5	5
Span (m)	>500	4	4
No. of lanes	>4	3	3
Age (years)	>50	4	4
Current rating	20-40	4	5
Additional service features	Above water	5	5
	Σ	**30**	**31**
Class II: Hazard likelihood (ψ_h = 0.23)			
Parameter	**Sub-parameters**	φ_h	$\varphi_{h(max)}$
Response time (min)	10-20	3	5
Historical significance	Prestigious	3	3
History of fires	Frequent	3	3
Fire scenario	Fire due to fuel freight ship collision with a bridge pier	5	5
	Σ	**14**	**16**
Class III: Traffic demand (ψ_t = 0.11)			
Parameter	**Sub-parameters**	φ_t	$\Phi_{t(max)}$
ADT	>50,000	5	5
Facility location	Urban	3	3
	Σ	**8**	**8**
Class IV: Economic impact (ψ_e = 0.13)			
Parameter	**Sub-parameters**	φ_e	$\varphi_{e(max)}$
Alt. routes	<10 km	1	3
Time expected for repair	>9 months	3	3
Cost expected for repair	1-3 million	2	3
	Σ	**6**	**9**
Class V: Expected fire losses (ψ_f = 0.09)			
Parameter	**Sub-parameters**	φ_f	$\varphi_{f(max)}$
Life/property losses	Many casualties	3	3
Env. damage	Unacceptable damage	3	3
	Σ	**6**	**6**

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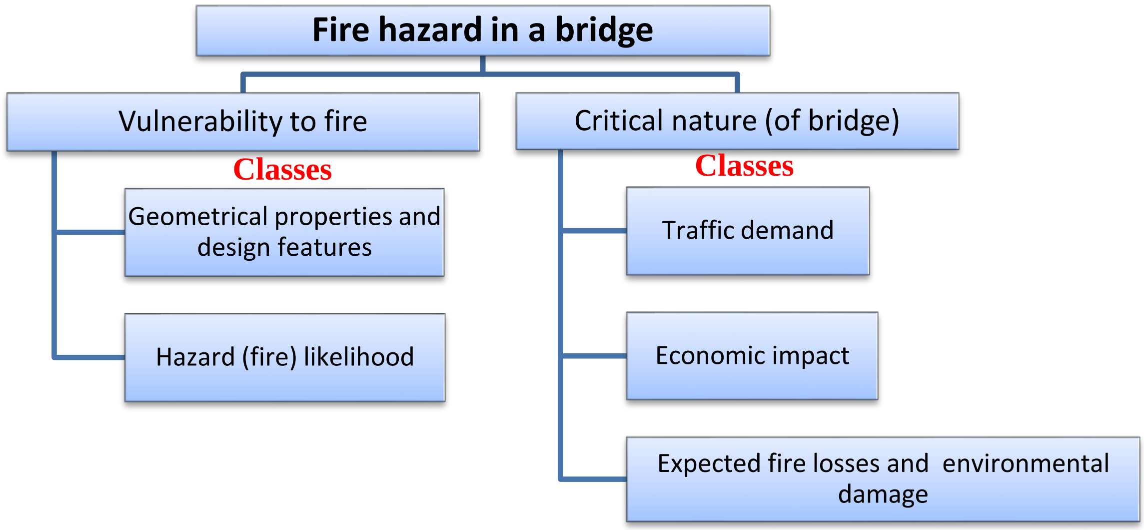

Fig. 1. Key characteristics influencing fire hazard in bridges

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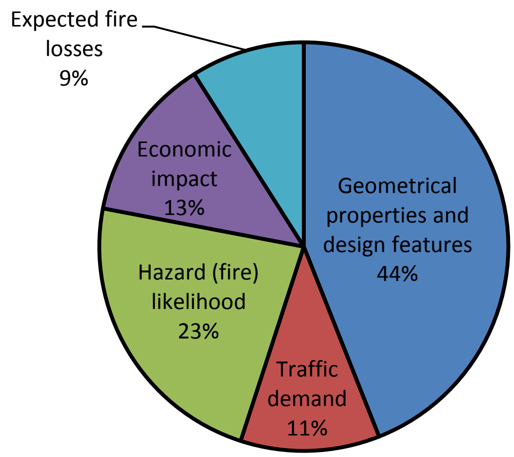

Fig. 2. Contribution of different classes (factors) to the overall importance factor

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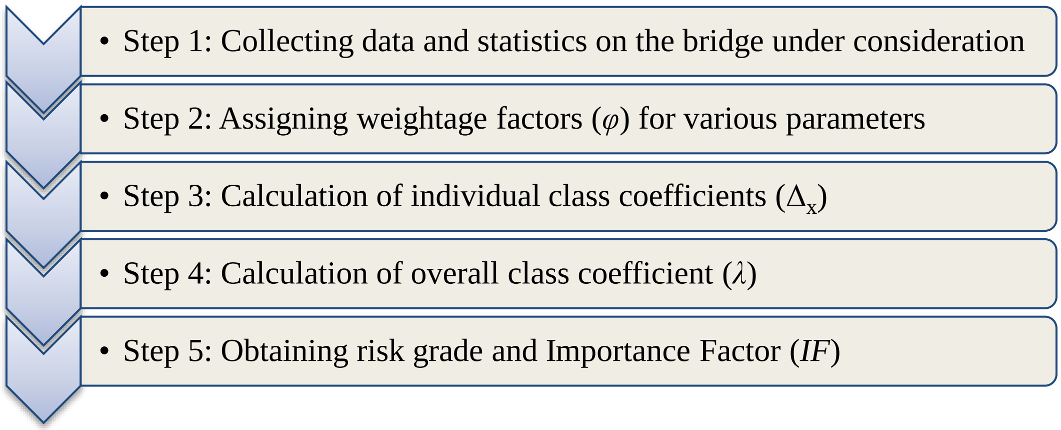

Fig. 3. Flow chart illustrating the steps involved for evaluating importance factor