EVALUATION METHODOLOGY OF THE ARGENTINEAN BRIDGE MANAGEMENT SYSTEM

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ABSTRACT

Bridges have important implications for economic, social, cultural, and military activities of a country because they give continuity to highways and roads. These implications depend primarily on the condition of the bridge.
Bridges have been found to present a combination of particular characteristics that are not commonly found in other civil works. This combination entails the structural, hydraulic, and traffic safety characteristics of the bridge. For this reason, the bridge condition should be considered from a global point of view, including the aforementioned aspects.
Therefore, a bridge in excellent condition means that it presents, simultaneously, a good structural and hydraulic condition, and it ensures a safe circulation of traffic across the bridge.
A Bridge Management System (BMS) called “SIGMA Puentes” was developed in order to aid authorities to properly administrate a budget for maintaining and repairing existing structures while accounting for the aforementioned aspects. It was created as the result of a joint effort by the National University of Córdoba and the National Highway Directorate of Argentina.
This paper presents a new methodology for assessing the condition of bridges from a global standpoint. Bridges are evaluated by taking into account structural, social, environmental, traffic safety, and economic aspects considering the bridge as part of a highway system.
The proposed evaluation methodology builds upon a group of risk and consequence indicators which give a global condition grade for the bridge. This grade is the principal parameter used to generate a prioritized list of rehabilitation, maintenance, or reconstruction necessities for the Argentinean National Highway System.

1. INTRODUCTION

Bridge management systems are used throughout the world in order to ensure safety and functionality of highway networks and to assist highway and bridge agencies to manage budgetary constraints to achieve optimum improvements to the bridge network (Kaschner et al., 1999; Czepiel, 1995). This requires a continuous activity of bridge agencies in order to gather important data regarding bridges characteristics and their condition. This is usually accomplished through bridge periodical inspections where information is systematically collected and stored in a computer database, generally, as part of a Bridge Management System. Field data is used to grade bridges condition which, in turn, is used to delineate a prioritized bridge maintenance program based on a cost-benefit analysis. The overall goal of the maintenance program is to maintain a certain level of safety and functionality of a highway network with a minimum long term cost (Woodward et al., 2001).
Numerous countries around the world have a Bridge Management System (BMS) which aids public authorities in their choice for optimum improvements of the highway bridge

network, and many of the existing BMS have been developed by consulting agencies and have been successfully implemented in different countries.
In spite of the several available BMS, it was decided to create a new BMS for the Argentinean National Highway Directorate (NHD) after a comprehensive review and analysis of existing BMS was made. Probably the most important factor considered in order to create a new BMS were some particular characteristics observed in the Argentinean highway networks.
These characteristics may be condensed in the following two aspects:
(a) Argentina may be considered a geographically large country (2.780.400 km^2) with almost 40000 km long national highway network having more than 3500 bridges under the jurisdiction of the NHD. Long distances would attempt to reduce agility in centralizing collected information of inspected bridges resulting in a delay to find solutions to urgent maintenance or retrofitting problems. This was believed to be one of the special issues considered essential in Argentina and helped to decide to create a new BMS since; and
(b) Many economic and social crises affected the country during the last 50 years which had an important impact in the construction and maintenance of road networks. As a result, an important percentage of the national highway network (including bridges) has deficient condition and presents an obsolete design considering actual international standards for highways. Many fatal accidents in Argentinean highways may be explained by obsolete geometric design.
Aspect (a) was solved through the creation of an internet-based BMS which allows to access information from any point of the country in real-time, allowing for accessing the bridge inventory and condition efficiently at any time. Finally, aspect (b) was addressed by including traffic safety within the evaluation of the bridge condition grade in order to highlight structures that may be in excellent apparent condition but have been found to present an obsolete design (such as narrow bridges, for example) resulting in an unsafe transit over the bridge.
Argentina has given the first step forward to implementing a BMS on its national highway network bridges. The developed BMS lacks of many currently available tools such as rate deterioration prediction, load carrying capacity estimation, and modern inspection technologies. However, it is expected that the NHD BMS would continue to being developed and updated in order to reach, in the near future, current international bridge management standards.
In the following sections of this paper, principal aspects of the BMS are described devoting special attention to the proposed procedure for evaluation of the bridge condition.

2. BACKGROUND

The implementation of BMS throughout the world has been promoted by governmental agencies in an attempt to maintain certain service and safety standards of bridges with a minimum long-term cost. This entails a proactive maintenance approach assisted with periodical bridge inspections and condition evaluation that would allow a more efficient budget administration resulting in a reduction of long-term maintenance costs of highway network bridges.
BMS are usually implemented through strong computational software which stores and administrates the bridge information database. The software stores relevant bridge information with the ultimate goal of generating a prioritized list of the most urgent repair works required for bridges included in the database. The prioritized repair works list is defined after applying a evaluation and ranking algorithm to all structures existing in the database at a certain time.
The bridge condition evaluation algorithm is one of the five principal parts or modules observed to conform most of the BMS studied for this paper. It was observed that most of

the existing BMS present similar characteristics considering the following structure composed of five modules: (1) Inventory, (2) Inspections, (3) Condition Assessment, (4) Repair costs estimation and maintenance options, and (5) Prioritized maintenance program. These five modules have been developed using different approaches and implemented using different tools and criteria.
However, modules (1) and (2) have been found to be conceptually similar between the different BMS analyzed. In spite of this, strong discrepancies for different BMS where detected in modules (3) through (5) resulting in a great variety of grading scales, grading rules and ranking algorithms. For this reason, this paper is devoted to describe the bridge condition grading or “Evaluation” methodology proposed for the NHD, which may be found to be substantially different from other existing methodologies. A detailed description of the entire NHD BMS and his complementary tools may be found in references [1] to [6], as well as a comparison of the grading and ranking methodology of several BMS currently existing in the world.

3. THE “SIGMA-P” (ARGENTINEAN BRIDGE MANAGEMENT SYSTEM)

There are more than 3500 bridges of different characteristics (steel bridges, concrete bridges, prestressed concrete bridges, arch bridges, etc.) and about a half of the bridge stock is located on main national highways.
Due to a lack of periodical maintenance and retrofitting activities of many structures lead them to a poor condition resulting in an unsafe traffic circulation and substantial economic losses due to bridge failure. Population growth and new automobile technologies and characteristics further exacerbate the traffic safety problem. In order to aid governmental agencies to rationally allocate retrofit and maintenance budget it was decided to development of specific Software (SIGMA-P) and a complementary Web Site.
The NHD BMS consists of five interrelated modules, as mentioned before, similarly to most of the existing BMS. The synthesized main structure of the BMS is illustrated in Figure 1.The process of the BMS may be summarized as follows: Modules 1 and 2 of the structure presented in Figure 1 consist of gathering all information regarding bridge characteristics and bridge condition, respectively. In Module 3 an overall bridge condition grade is obtained from information collected in Modules 1 and 2. Recommendations for rehabilitating, retrofitting or replacing the bridge are given at this point. Module 4 consists of estimating costs of the selected rehabilitation strategy. Finally, and using bridge grade and cost estimation (from modules 3 and 4, respectively) a ranking list of rehabilitation, retrofitting, or replacement works is defined in Module 5.

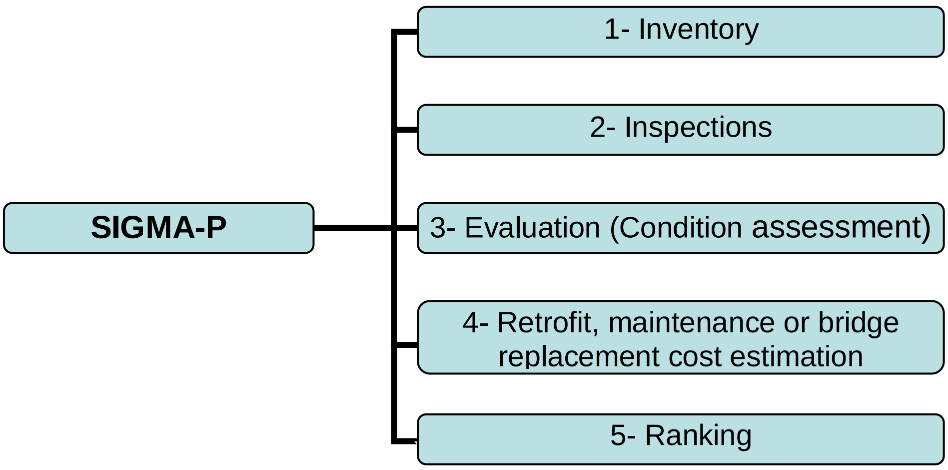

Figure 1 – Synthetic structure of the NHD BMS

As mentioned before, this paper focuses in Module 3 of the BMS paying special attention to the proposed approach for evaluating the bridge condition grade, as well as the risk and consequences of failure. Modules 1, 2, 4, and 5 do not differ substantially from other existing BMS.

4. METHODOLOGY FOR GRADING BRIDGE CONDITION

A review of a series of BMS currently in use around the world was carried out during the initial phase of the project conducted by the National University of Córdoba (NUC) and NHD. It was found a wide variety of methodologies and approaches for grading bridge condition. In some cases, the evaluation methodologies involved complex algorithms used to obtain the final grade of a bridge. In addition to this, it was found that some countries had practical implementation problems, some of which may be explained by excessively complex software or grading methodology. For these reasons the project conducted by the NUC sought to develop a simple but conceptually strong BMS which would facilitate a rapid and easy implementation of the system throughout the country with minimal requirements of investment in human resources and equipment.
The proposed methodology considers that a bridge may be evaluated from three different points of view: (a) Structural standpoint, (b) Hydraulic and Environmental standpoint, and (c) Traffic Safety standpoint.
The study of different bridges in the national highways of Argentina indicated that “Bridge Failure” may be explained by any of these aspects. The term “Bridge Failure” was considered in this project within a broad sense, including any situation leading to an abrupt decrease in the service level of the bridge, not necessary meaning collapse of the structure. Because of this, load carrying capacity limitation, unsafe circulation, or a bridge temporarily out of service, are considered herein as situations of “Bridge Failure”.
A bad structural condition may lead to bridge collapse due to loads imposed on the structure (wind, earthquake, or traffic) meaning large economic losses and, eventually, human casualties. In the same way, a bad hydraulic design of the bridge or bad condition of bridges scour preventive works over rivers and waterways may lead to bridge collapse due to unexpected scour of piers and abutments affecting their foundations, unexpected large hydrodynamic forces on the structures, or impact of big river debris on structural components of the bridge. The third standpoint considered to evaluate bridge condition is traffic safety. Although a bridge would not literally collapse due to unsafe traffic circulation, it was considered that an unsafe circulation (characterized by, for example, number of fatal accidents on the bridge or in the approach zone of the structure) would also entail “Bridge Failure” since the bridge would fail to achieve one of its main functions.
Considering the aforementioned aspects, the proposed evaluation methodology is based on a group of failure risk and failure consequences indicators, which assign a global condition grade for the bridge. Risk indicators are intended to quantify the possibility of bridge failure due to a bad structural, hydraulic, or traffic safety condition. Grades are assigned to the three failure risk indicators to individually assess the structural, hydraulic, and traffic safety condition of the bridge. The weighted average of these grades gives the bridge Failure Risk Grade (FRG).
The assessment of the bridge failure consequences is achieved through the quantification of three failure consequences indicators that allows for estimating the Failure Consequences Grade (FCG). This grade is the principal parameter upon which a priority list for the execution of rehabilitation, maintenance, or retrofit of existing bridges is defined in the NHD BMS.

4.1. Failure Risk and Failure Consequences indicators

It was stated in the previous section that two groups of indicators involving a total of six parameters were to be evaluated in order to arrive to a final bridge condition grade. The first group, named Failure Risk indicators, consists of the following three indicators: Structural failure indicator (SFI), Hydraulic failure indicator (HFI), and Traffic Safety failure indicator (TSFI). The weighted average of individual grades of the three parameters gives the Failure Risk Grade (FRG). Weight factors for each indicator were determined after several discussions and analysis of the most common bridge characteristics in Argentina by specialists of the NUC and NHD. The proposed weight factors at the present are: SFI = 30%, HFI = 30% and TSFI=40%. Using the above weight factors, the equation for determining the FRG may be expressed as:

$$FRG = 0.3 \times SFI + 0.3 \times HFI + 0.4 \times TSFI$$

Guidelines for the estimation of structural, hydraulic, and traffic safety indicators were developed in order to aid professionals and specialists in grading the FRG for bridges. A summary of these guidelines is presented below. Values for the SFI and HFI are assigned for each bridge according to the guidelines given in Table 1. The proposed grading for the TSFI is presented in Table 2.

Grade	Proposed evaluation criteria
1	For indicators which entail high possibility of bridge closure
3	For indicators which entail high possibility of limiting bridge carrying capacity
5	For indicators which entail high costs arising from urgent retrofitting operations
7	For indicators which do not entail high costs arising from urgent retrofitting operations
9	For indicators which only entail routine and usual rehabilitation or maintenance operations

Table 1 - Proposed grading scale for SF and HF indicators

Grade	Proposed evaluation criteria
1	For bridges were fatal accidents have been registered in the last three years, bridges with inadequate geometric design (i.e. problems of visibility)
3	For bridges with an usable width narrower than highway width before and after the structure and bridges were an important reduction of traffic velocity has been observed
5	For bridges with an usable width less than 8.30 m and for bridges were a small reduction of traffic velocity has been observed
7	For bridges not falling in the above categories and having need of repairing or replacing vehicular railing or pedestrian railings
9	For all bridges which only need routine maintenance, such as railings painting

Table 2 - Proposed grading scale for TSF indicator

In order to ensure high serviceability levels for bridges, an FRG equal to 7 was defined as threshold such that a FRG below 7 represents a medium failure risk bridge. Contrary to that, an FRG equal or larger the threshold represents a low failure risk bridge. All structures having a FRG less than 6 are deemed to present an unacceptable condition (high failure risk), and the evaluation of the consequences of bridge failure should be evaluated (it is worth to note that an FRG less than 6 indicates a bridge which needs imminent attention, but the grade does not necessary indicates that the bridge is near collapse). In addition, bridges for which any of the Failure Risk Indicators is equal or less than 5 are also deemed to present an unacceptable condition even though the FRG for these cases may give an average grade above 7.

Assessment of bridge failure consequences is achieved through the Failure Consequences Grade (FCG), which is obtained as a result of the weighted average of three Failure Consequences Indicators. These indicators are Highway network vulnerability (HNV), Strategic Bridge Value (SBV), and Annual Average Daily Traffic (AADT). The originally proposed weight factors are: HNV = 30%, SBV = 30% and AADT=40%. Following the same criteria as for obtaining the FRG, the weighted average of FCI may be expressed as follows:

$$FCG = 0.3 \times HNV + 0.3 \times SBV + 0.4 \times AADT$$

For bridges having high or medium failure risk (FRG less than 7) only due to a low TSI grade, the Highway Network Vulnerability would not be affected by bridge failure, thus prior expression would be modified as follows:

$$FCG = 0.45 \times SBV + 0.55 \times AADT$$

The FCG is the principal parameter used by the NHD BMS to define a list of priorities for rehabilitation and retrofitting existing bridges. The FRG value is an indicator of the failure risk of the bridge, while the FCG value indicates the suggested order in which bridges should be retrofitted or replaced in order to ensure a high service level of the highway network at minimum long term cost. Since low values of FCG indicate high priority bridges the ranking list is ordered so the bridge with the lowest FCG would be on the top of the prioritized list. The FCG is calculated upon the individual values of three indicators using previous expressions, so grades for these indicators would vary depending on the importance of the bridge. For this reason, bridges with voluminous traffic, or placed in an economically or socially important road network segment, or in a strategic environmental protected area, would have low Failure Consequences Indicators grades so that the bridge will result in a high position within the priority list. The proposed grades for the Failure Consequences Indicators are presented in the following section.

4.2. Failure Consequences indicators

Failure consequences indicators are intended to quantify costs arising from bridge failure considering user costs, material costs due to bridge collapse, and environmental costs that may be originated for bridges in special environmental locations. The three proposed Failure Consequences Indicators are: (a) Highway network vulnerability (HNV), (b) Strategic Bridge Value (SBV), and (c) Average Annual Daily Traffic (AADT). In this section, a brief description of these indicators is given. A detailed coverage of this topic may be found at [5] y [6].

Indicator (a) is intended to evaluate economic losses that arise from a limited bridge carrying capacity or bridge closure would force users to choose alternate ways to complete certain tour. This indicator was also incorporated in the system in order to consider the fact that bridge collapse would have an important negative impact on the entire highway network since the continuity of the system would result interrupted. Important negative economic consequences would affect several regions.

An example of this was the failure of the bridge over the Seco river in January of 2006 that resulted in a two weeks isolation of more than 7 towns and cities located in Salta province (Argentina).

In order to quantify this factor, it was assumed that the longer the alternate tour required for joining two points of the highway network in which the bridge is located, the greater the economic losses turn to be. The range of values to be assigned to the HNV indicator is showed in Table 3 where the extra length involved in the alternate tour required to arrive to the original destination is expressed in terms of both additional required distance and additional required time to complete the alternate tour.

HNV	Additional time for using alternate way [min]	Additional distance for mean velocity of 15 km/h [km]	Additional distance for mean velocity of 40 km/h [km]	Additional distance for mean velocity of 80 km/h [km]
1	> 120	> 30	> 80	> 160
3	60	15	40	80
5	30	7.5	20	40
7	15	4	10	20
9	< 7	< 2	< 5	< 10

Table 3 - Grading scale for the Highway Network Vulnerability Indicator

Indicator (b) was defined in order to take into consideration in the evaluation process the social, economic, geopolitics, and environmental significance of the highway system segment in which the bridge is located. It was found that all the aforementioned aspects may be condensed into the SBV indicator through the application of the following expression:

$$SBV = SBV_0 - Z_u - Z_f - E$$

SBV_0 is a reference value for this indicator, taken from Table 4; Z_u is the Urban Zone factor; Z_f is the Frontier Zone factor; and E is the Environmental Vulnerability factor. These factors are described in the following paragraphs.

SBV_0	Description
5	Principal highway
7	Non-paved roads or secondary highways
9	Secondary non-paved roads

Table 4 - Reference values for the evaluation of Strategic Bridge Value

Factor Z_u considers that bridges located near urban zones play a socioeconomic role that may be more important than its road function. For this reason, bridges near highly populated cities would have high Z_u factors resulting in lower SBV values. Proposed values for Z_u are showed in Table 5.

Z_u	Description
0	Rural zone
1	City Population < 2000 habitants
2	2000 < City Population < 10000 habitants
3	10000 < City Population < 100000 habitants
4	City Population > 100000 habitants

Table 5 - Proposed values for Urban Zone Factor

Factor Z_f considers that bridges located near international borders or in international highway play a geopolitical and economical role that may be more important than its road function. For this reason, bridges near international frontiers would have high Z_u factors resulting in lower SBV values. Proposed values for Z_f are showed in Table 6.
Finally, the Environmental Vulnerability factor (E) was incorporated in the methodology to consider the environmental sensibility of the area in which the structure is located. Environmental sensibility may be Low, Moderate, or High as shown in Table 7.
The proposed methodology for evaluating FCG considers that the sum of factors Z_u, Z_f, and E should not be larger than 4, thus an integral evaluation of the SBV should be performed.

Z_f	Description
0	Located at more than 400 km from international frontier and the bridge does not lie on international road
1	Located at more than 400 km from international frontier and the bridge lies within an international highway
2	Located between 200 and 400 km from international frontier
3	Located between 100 and 200 km from international frontier
4	Located at less than 100 km from international frontier

Table 6 - Proposed values for Frontier Zone Factor

E	Description
0 - 1	Low
2	Moderate
3 - 4	High

Table 7 - Proposed values for Environmental Vulnerability Factor

The last Failure Consequence Indicator is the AADT. This parameter measures the average quantity of vehicles that cross the bridge annually, allowing for estimating the quantity of users affected by bridge collapse. The grading scale of the AADT factor is such that bridges with high traffic will have low values, as showed in Table 8.

Grade	Description
1	AADT > 5000 vehicles/day
3	3000 < AADT ≤ 5000 vehicles/day
5	1500 < AADT ≤ 3000 vehicles/day
7	500 < AADT ≤ 1500 vehicles/day
9	500 < AADT vehicles/day

Table 8 - Grading scale for the Average Annual Daily Traffic Indicator

Intermediate values for grades shown in all tables in this paper may be assigned to each indicator according to particular situations for a bridge under evaluation that are explained in references.

The proposed methodology for grading bridge condition in the SIGMA-P may be summarized as follows: Having stored in the BMS database the inventory and inspection information of a bridge, the evaluation of its conditions is performed. The evaluator starts grading the three Failure Risk indicators. If any of these indicators is equal or less than 5, the bridge is deemed to present bad condition and is entitled as a “High Failure Risk Bridge”. If the three indicators are larger than 5, the weighted average of the individual grades is carried out. If this average is below 6, the bridge is also deemed to present bad condition.
Finally, if the bridge is a High Failure Risk Bridge, the evaluator proceeds to grade the Failure Consequences Indicators. After grading the second set of indicators, the BMS software computes the FCG and includes the bridge in the prioritized list or ranking of bridges existing in the BMS database according to the FCG obtained.

5. SUMMARY AND CONCLUSIONS

In this paper a brief summary of the recently developed Argentinean BMS was presented. The BMS is composed of five modules, similarly as many existing systems around the world. This paper focused on the third and fifth modules which are the Bridge Condition

Assessment and Ranking, respectively. The main distinctive characteristic of the proposed BMS is the bridge global condition evaluation and the use of a series of indicators to define a priority list for the execution of rehabilitation, maintenance, or retrofit of existing bridges of the Argentinean National Highway network.
Two sets of indicators were defined in order to obtain the priority list or ranking. The first set of indicators, Failure Risk Indicators (FRI), are intended to quantify the possibility of bridge failure considering that a bridge may be assumed to have collapsed due to any of the following situations: bad condition of its structure, bad condition or inadequate design of bridge hydraulics, or due to a highly unsafe traffic circulation through the bridge. In the proposed BMS the terms “Bridge Failure” or “Bridge Collapse” are used in an ample sense, meaning that a bridge may be considered collapsed or failed if it does not satisfy at least one of its principal functions. In this regard, it was assumed that a safety of traffic circulation is one of the most important functions of the bridge. The traffic safety factor was included in the evaluation process due to the particular characteristics of some Argentinean highways.
The weighted average of the FRI gives a Failure Risk Grade (FRG). This grade is used to separate bridges with high or medium failure risk (FRG less than 7 or any of the individual Failure Risk Indicators is smaller than 5) from bridges with low failure risk (FRG equal or greater than 7). For low risk bridges only maintenance work is recommended. For high failure risk bridges, the consequences of bridge failure (due to any of the aforementioned indicators) should be evaluated. The evaluation of failure consequences is carried out by means of the second set of indicators: Failure Consequences Indicators. The weighted average of these indicators or Failure Consequences Grade (FCG), gives the final grade upon which a priority list for the execution of rehabilitation, maintenance, or retrofit of existing bridges of the Argentinean National Highway System is defined. The FRG may vary from 1 to 10. In the other hand, the FCG may vary from 1 to 9, where a 1 means that very important negative consequences may arise from bridge collapse and bridges with low FCG would appear on top of the ranking list. The recommended values for all indicators were described in this paper.
It is worth to note that these values may vary if the system is to be used in different regions in order to appropriate reflect local highway network and traffic conditions. The implantation of the proposed BMS is being currently carried out in Argentina.

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