DETERMINATION OF A FUNCTIONAL INDEX FOR BRIDGES

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ABSTRACT

Bridges are crucial assets forming part of road infrastructure. One of the challenging problems faced by bridge engineers and road asset managers is maintaining these bridges in such a way that they do not only meet optimum condition requirements, but also those requirements that are concerned with the functionality of the bridges. Various indicators, such as the Priority Condition Index, are used to indicate the condition of bridges and to develop a maintenance strategy for bridges, but similar indices for the functionality of bridges are not available. This paper focusses on the need for a functional index for bridges and presents a method to calculate a combined Bridge Functionality Index (BFI) based on traffic volumes accommodated by the bridge and the functional ratings of the detour route that would have to be used should the bridge fail. The proposed BFI was tested on 10 bridges on the Gauteng provincial road network. The study methodology involved identifying the bridges, determining the detour routes and analysing traffic data for the roads over the bridges and for the detour routes. This was followed by the development of the BFI, which is a weighted combination of a Traffic Volume Factor for the road over the bridge and a Functional Index for the detour route. The Functional Index for the detour route is a function of five factors, namely User Risk Factor; Road Capacity Factor; Riding Quality Factor; Road Safety Factor; and Detour Length Factor.

1. BACKGROUND AND INTRODUCTION

Bridge assessments is an integral components of bridge rehabilitation, maintenance and management. Financially effective maintenance strategies that are developed through the application of Bridge Management Systems (BMS) are dependent on accurate bridge assessments. A BMS forms an integral part of a Road Asset Management System (RAMS). One of the outputs from a BMS is a condition index that describes the condition of a bridge from an engineering point of view (Roux, 2016). An example of such a conditional index is the Priority Condition Index (PCI) that is calculated using the degree, extent and relevancy ratings of defects on bridges, as described in the COTO TMH 19 Manual for the Visual Assessment of Road Structures (COTO, 2019).

In addition to condition indices, the draft COTO manual, TMH 22 Road Asset Management Manual (COTO, 2013) also prescribes the calculation of functional indices that are based on an appraisal of road infrastructure in terms of functional characteristics that affect the quality of use, convenience, safety, congestion and operational costs. These functional indices rate the infrastructure from the point of view of users. Methods to calculate functional indices have been well developed for road pavements. TMH 22 contains methods to calculate four functional indices for road pavements, namely capacity; riding quality; user risk; road safety; and availability. TMH 22 however does not include a method for calculating functional indices for road structures, such as bridges.

This paper describes a method to calculate a functional index for bridges and focuses on the impact resulting from a bridge having to be taken out of service. This index therefore focusses on the availability aspect of functionality. The main consideration in the proposed method is the effect of the unavailability of the bridge on traffic and the extent to which the detour routes are able to serve the diverted traffic. To serve in this context mainly relates to the travel experience on the detour route until the user re-joins the road link on which the bridge is located. Factors to be considered are the effect on the quality of use, convenience, safety, congestion and operational costs caused by the bridge being unavailable for use and traffic therefore travelling on the detour route. A good example of this scenario is the recent closure of the M2 freeway in Johannesburg for eight months due to serious defects detected on the Kaserne Bridge.

2. STUDY AREA

Ten bridges were selected on the Gauteng provincial road network for the testing of the proposed method to calculate the BFI. The ten bridges are listed in Table 1.

The length of the Gauteng provincial road network in terms of carriageway-km, is 5 719 km, with 4 452 km (78%) paved and 1 266 km (22%) unpaved. The split between rural and urban roads is 3 774 km (65%) rural and 1 975 km (35%) urban. The Gauteng provincial road network includes 676 bridges and 428 major culverts.

The traffic volume distribution per road class is illustrated in Figure 1, showing that the principal and major distributors/arterials carry approximately 74% of the traffic volume on the provincial road network. Hence, the selected bridges for this study are situated on either principal or major distributors/arterials.

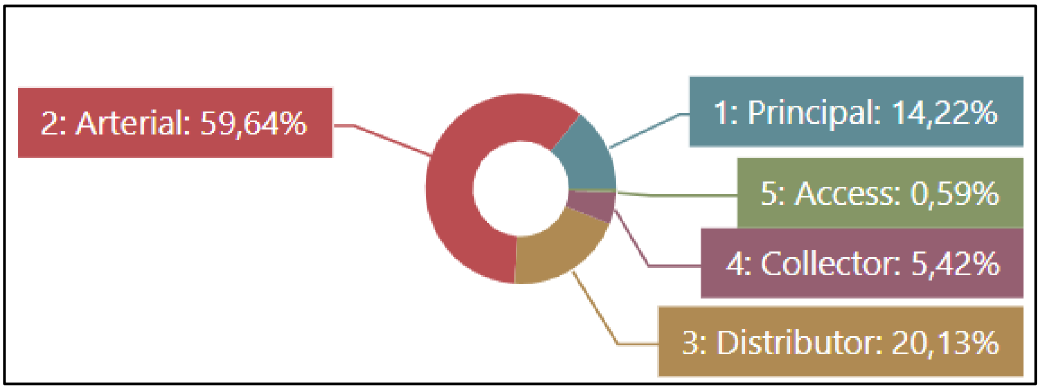

Figure 1: Vehicle-km distribution by road class

Table 1: Sample of 10 Bridges selected for the study

Bridge ID	Road Link	Maintenance Region	Bridge AADT
1	P95/1_010	Krugersdorp	1 670
2	P207/1_010	Krugersdorp	670
3	D2612_020	Vereeniging	1 128
4	D64_050	Vereeniging	847
5	D1132_020	Benoni	3 198
6	P101/1_020	Benoni	899
7	D1386_050	Pretoria	2 344
8	D2666	Pretoria	901
9	P611_080	Bronkhorstspruit	1 334
10	K175_010	Bronkhorstspruit	536

3. DATA COLLECTION

The bridge data for the ten bridges was obtained from the Gauteng BMS (STRUMAN). Detours for each of the ten bridges and the lengths of these detours were identified using the Gauteng RAMS Geo-spatial Decision Support System. Traffic data was obtained from the Gauteng RAMS Geo-spatial Decision Support System, while the condition of the roads comprising the detours was obtained from the Gauteng PMS.

4. METHODOLOGY

The methodology developed in this study is presented in Figure 2.

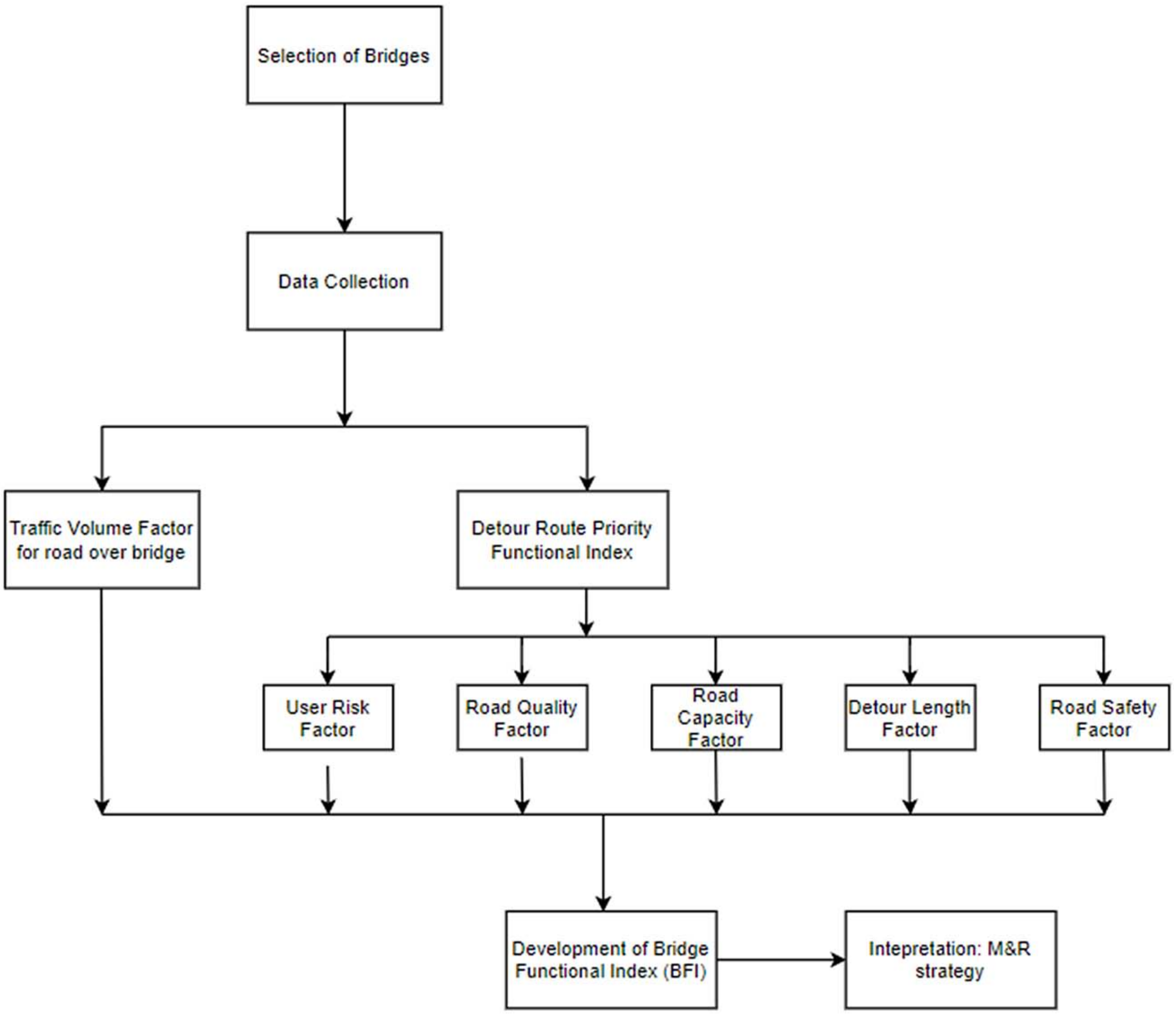

Figure 2: Methodology for Calculating the BFI

4.1 Calculation of Traffic Volume Factor

The Traffic Volume Factor (TVF) is adopted from TMH 22 (COTO, 2013). The TVF considers the volume of traffic that will be affected should the bridge fail. The TVF is determined from the ADT value for the road link on which the bridge is located, using the factor values presented in Table 1. It is important to note that Table E-17 in TMH 22 allocates a higher factor value the higher the ADT value. For the purposes of calculating the TVF as input for the BFI, the higher the ADT value on the detour route, the lower the factor value should be. The factors in Table 2 are therefore the inverted TMH 22 Table E-18 values.

Table 2: Modified Traffic Volume Factor Values. (TMH 22, COTO Draft, 2013)

ADT	Factor Value
ADT ≥ 10 000	50
5 000 ≤ ADT ≤10 000	70
1 000 ≤ ADT ≤5 000	80
500 ≤ ADT ≤1 000	90
ADT ≤ 500	100

4.2 Calculation of the Detour Route Functional Index

The functional evaluation of the detour route is based on four of the functional indicators that are used in road asset management systems, namely user risk, capacity, riding quality and road safety. These indicators are adopted from TMH 22. (COTO, 2013). The length of the detour was also deemed an important factor in the functional evaluation of the detour route. A Detour Route Length Factor (DRLF) was thus added. The calculation of the five factors, which go into the calculation of the Detour Route Functional Index, is described in the following sections.

4.2.1 User Risk Factor (URF)

The user risk factor is used to quantify the risk to road users when using the detour route. It is important to understand that road safety depends on many factors, such as (COTO, 2013):

- Driver behaviour;
- Driver information;
- Law enforcement;
- Vehicle factors;
- Visibility factors;
- Road surface and shoulder condition; and
- Road Geometry.

Any one of the above factors can override all others. Considering the wide range of inspections and measurements that form part of a RAMS, as well as the most significant network level factors that signify risk, the following risk factors have been identified in TMH 22 (COTO, 2013):

- Skid risk as a function of road surface skid resistance;
- Safety related to road roughness; and
- Safety risk related to road width.

The calculation of the functional ratings related to each of these risks as well as the composite index for all three is described in section E.3.5 of TMH 22 (COTO, 2013) and is not repeated here. The scope of the study was limited in terms of the data required to calculate this factor and for the purpose of this paper, the User Risk Factor was taken as 50 to maintain neutrality.

4.2.2 Road Capacity Factor (RCF)

The road capacity is dependent on the cross section, geometric alignment as well as passing opportunities and intersection spacing. For the purposes of this study, the method to calculate a road capacity factor as presented in TMH 22 was adopted. The method in TMH 22 is based on the Highway Capacity Manual and the output is a capacity functional index ($FI_{v/c}$), based on the volume/capacity ratio of a road.

The traffic volume is expressed in terms of Equivalent Vehicle Units (EVUs) per day. The equation to calculate EVU is as follows:

$$\boldsymbol{EVU\ PER\ DAY} = \boldsymbol{AADT} + (\boldsymbol{PCE} - \mathbf{1}) \times \%\boldsymbol{Hvy} \times \boldsymbol{AADT}$$

Where: *AADT =* *Average Annual Daily Traffic;*
%Hvy = *Percentage of heavy vehicles and;*
PCE = *Passenger car equivalency per heavy vehicle depending on the topography of the road. The PCE values according to COTO, 2013 are presented in Table 3.*

Table 3: PCE values, TMH (COTO, 2013)

Topography	**Passenger car equivalency per heavy vehicle**
Flat	3
Rolling	5
Mountainous	8

The capacity is calculated using the lane capacity for different road types, as presented in TMH 22 (COTO, 2013) and included here as Table 4.

Table 4: Lane Capacity for different Road Types (EVU/lane/hour) (COTO, 2013)

Topography	**Road Type**				
	Track	**Gravel**	**Paved 2-Lane**	**Dual Un-divided 4-Lane**	**Freeway**
Flat	20	50	1 000	1 500	2 000
Rolling	15	30	800	1 200	1 800
Mountainous	10	20	500	1 000	1 500

The volume/capacity ratio is normally determined for peak hour in the case of urban roads. EVU in the peak hour is determined by multiplying the above result with the following peaking factors presented in TMH 22 (COTO, 2013):

- Rural road: 15% for volume in the 30^{th} highest hour of the year.
- Urban road: 10% for volume in the peak hour.
- Rural with high-holiday traffic: 20% for volume in the 30th highest hour of the year.

Using the volume/capacity ratio, the functional index for V/C ($FI_{v/c}$) is calculated using the equation in TMH 22, as illustrated in Figure 3.

The Road Capacity Factor (RCF) is taken as equal to $FI_{v/c.}$

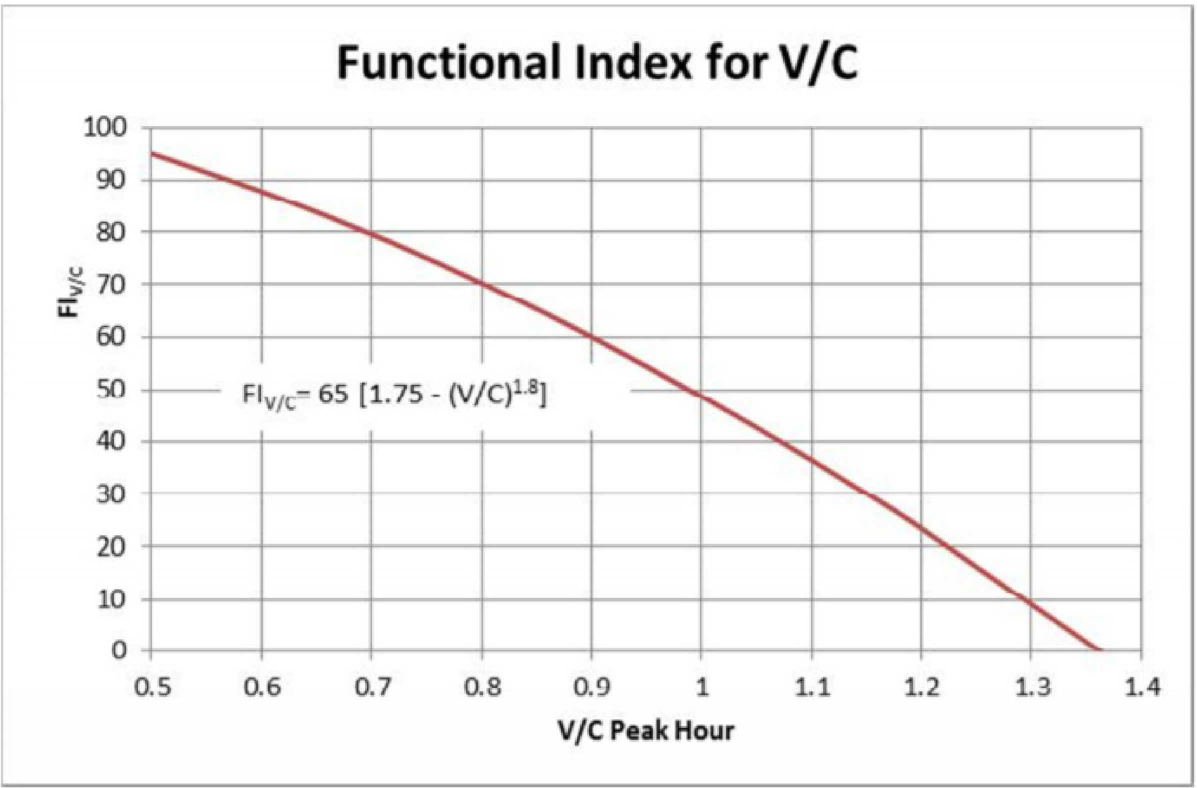

Figure 3: Functional Index for Volume/Capacity Ratio

4.2.3 Riding Quality Factor (RQF)

The riding quality of a road link (asset) is expressed in terms of IRI with measured values per 100 m segment. To determine the RQF, the average of the IRI values for the road links making up the detour route is calculated. This weighted average value is then used to calculate the RQF using the equation for FI_{IRI} in Figure 4.

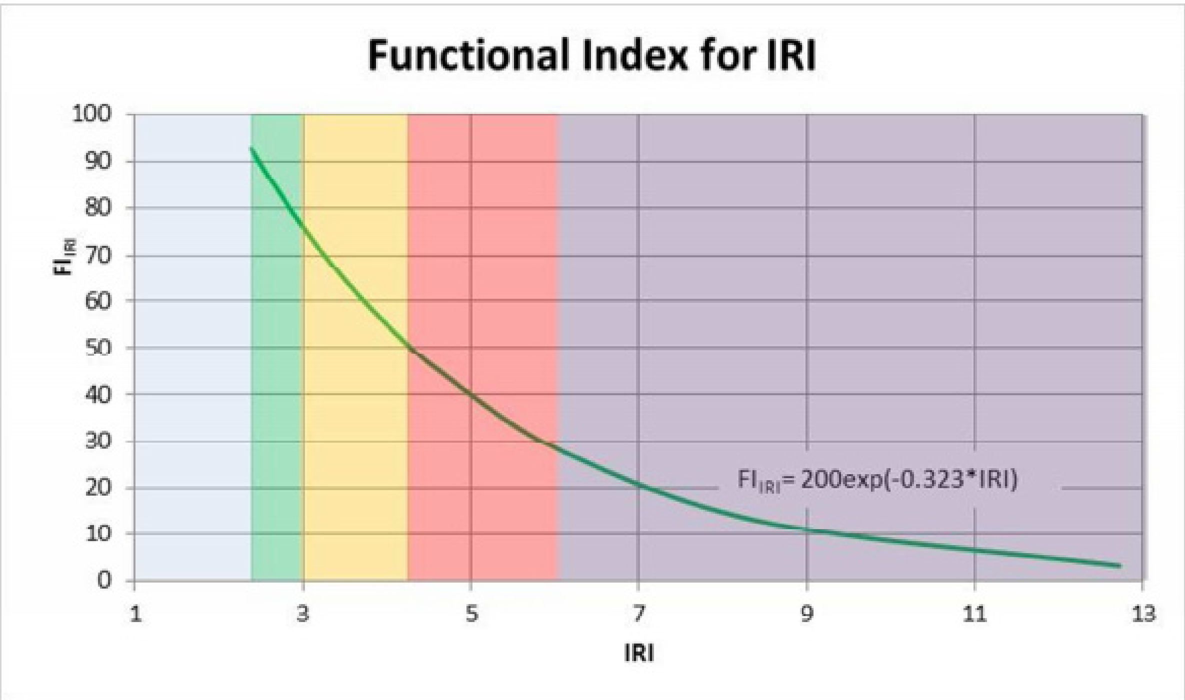

Figure 4: Functional Index from International Roughness Index

4.2.4 Road Safety Factor (RSF)

The safety record of a road is calculated as the number of accidents that occur relative to the traffic volumes on the road. This is normally expressed as the Personal Injury Accident (PIA) rate in PIAs per 100 million vehicle-kilometres (vkm). Normally, only the PIA is used because records for "damage-only accidents" are poor and the location records of these accidents are also not reliable. (COTO, 2013)

In the absence of reliable records, the typical average PIA for a specific road can be calculated using the following equation for South African conditions:

$$PIA_R = (R_{base} + R_{intersections} + R_{median}) \times fc \times fv \times fl \times fs$$

Where:

PIA_R = *PIA Rate = number of personal injury accidents per 100 million vkm*

R_{base} = *base accident rate (24 for multi-lane highways, 34 for surfaced single carriageway roads and 75 for single carriageway gravel roads)*

$R_{intersection}$ = *0 if intersections are grade-separated, or 30 if intersections are at-grade*

R_{median} = *0 if median is 18 m or wider 0 if median is 18 m or wider, or contains a guard rail or New Jersey barrier, varying linearly to 15 at a median width of 0 m, i.e. no median*

fc = *adjustment factor for curvature: 1.15 if curves are sharp, and 1.00 if curves are flat*

fv = *adjustment factor for verges: 0.80 if verges are very accommodating, and 1.00 if verges are narrow*

fl = *lane width adjustment factor, varying as shown in Table E-14 of TMH 22 (COTO, 2013)*

fs = *shoulder adjustment factor, varying as shown in Table E-14 of TMH 22 (COTO, 2013.)*

Table 5, which has been adopted from TMH 22, COTO Draft, 2013 shows the typical PIA base rates that can be used at a network level to identify problematic road links.

Table 5: PIA Base Rates

Topography	Gravel	Paved 2-lane	Dual	Freeway
Flat	75	70	54	24
Rolling	90	80	60	27
Mountainous	100	90	70	30

The ratio of PIA_{actual} to PIA_{base} is used to calculate a functional index as shown Figure 5.

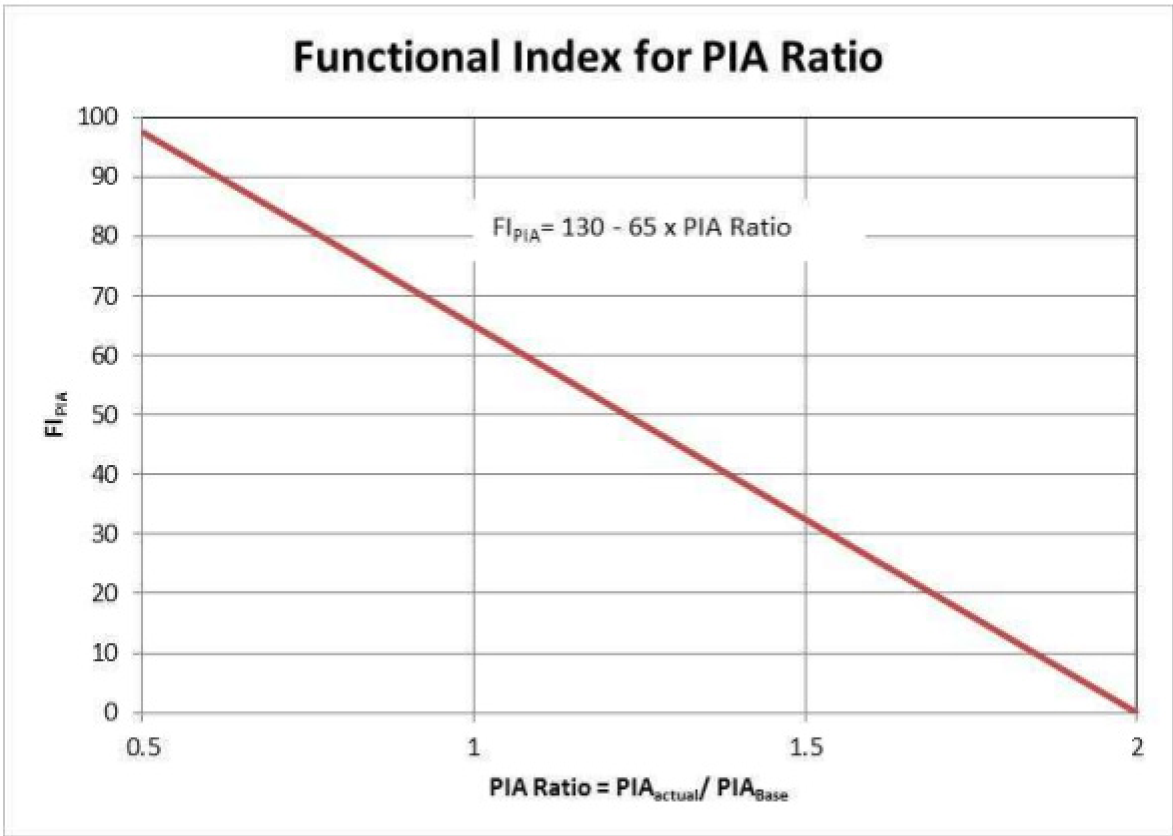

Figure 5: Functional Index based on Personal Injury Accidents (PIA)

The Road Safety Factor (RSF) is taken as equal to FI_{PIA}

4.2.5 The Detour Length Factor (DLF)

The DLF takes into account the total length of the individual roads that form the detour route, should the bridge fail. Table 6, adopted from TMH 22 (COTO, 2013), shows the conversion of the route length to a detour length factor. It is important to note that Table E-18 in TMH 22 allocated a higher factor value the longer the detour route. For the purposes of calculating the DLF as input for the DRFI, the longer the detour route, the lower the factor value should be. The factors in Table 6 are therefore the inverted TMH 22 Table E-18 values.

Table 6: Modified Detour length factor values (modified from COTO, 2013)

Detour Length (km)	Factor Value
DL≥100	50
50 ≤DL ≤100	60
20≤ DL ≤50	70
10≤ DL ≤20	90
DL≤ 10	100

4.3 Calculation of the Bridge Functionality Index

The study is concerned with the availability of the bridge and the functionality thereof. A bridge that is available for use is deemed fully functional, as there would not be a need to use a detour, while a bridge that is not available for use is fully non- functional. With the availability of a detour route, a road user will at least be able to continue with the journey and the availability of the detour route thus enhances the functionality of the bridge. Therefore, a bridge that is not available for use, but for which a detour route is available, is deemed to be semi-functional. To account for the availability or not of a detour route, the Bridge Functional Index is calculated as a weighted average of the Traffic Volume Factor and the Detour Route Functional Index. A weighting of 50% is used for each factor

To combine the five factors included in the calculation of the Detour Route Functional Index, a weight was allocated to each of these 5 factors to reflect the relevant importance of each factor. Importance weights are usually calculated through multi criteria assessments. It is calculated by means of normalized weighted values linked to the specific parameters, (COTO, 2013). The importance weights used for this study were based on Table E-15 of TMH 22 (COTO, 2013). The weights allocated to the various factors used in the calculation of the BFI are presented in Table 7.

Table 7: Factor Weights for Calculating BFI

Component	Factor	Description	Weight
Detour Route	DLF	Detour Length Factor	0.08
	RCF	Road Capacity Factor	0.16
	RSF	Road Safety Factor for the detour	0.16
	URF	User Risk Factor for the detour	0.08
	RQF	Riding Quality Factor for the detour	0.03
		Aggregate	0.50
Bridge	TVF	Traffic Volume Factor for the bridge	0.50
Bridge + Detour Route		Aggregate	1.00

The equation that was developed to calculate the BFI is as follows:

$$BFI = 0.5 \times TVF + (0.08 \times DLF + 0.16 \times RCF + 0.16 \times RSF + 0.08 \times URF + 0.03 \times RQF)$$

Where: *TVF =* *Traffic Volume Factor for the bridge*

DLF = *Detour Length Factor*

RCF = *Road Capacity Factor*

RSF = *Road Safety Factor for the detour*

URF = *User Risk Factor for the detour*

RQF = *Riding Quality Factor for the detour*

5. WORKED EXAMPLE

The procedure to calculate the OBFI for any bridge is illustrated with reference to Bridge 5 in Table 1. The ADT for the road over the bridge is 3 198. A detour route is available for Bridge 5 and it has a length of 2.5 km (from the GDRT's GIS) and an ADT value of 4 157. The ADT values were obtained from the GDRT's TIS.

The procedure to calculate the Bridge Functional Index requires six steps.

Step 1: Calculate the Traffic Volume Factor (TVF) for the bridge:

The ADT for the road over the bridge is 3 198 and as such falls in the category 1 000 ≤ ADT < 5 000.

From Table 2, the **TVF = 80**

Step 2: Calculate the Detour Length Factor (DLF):

The length of the detour is 2.5 km, and as such falls in the category DL < 10 km.

From Table 6, the **DLF = 100**

Step 3: Calculate the Road Capacity Factor (RCF):

The EVU in the peak hour of the detour route can be calculated according to Section 4.2.2 as follows:

$$\boldsymbol{EVU\ peak\ hour} = (\boldsymbol{AADT} + (\boldsymbol{PCE} - \mathbf{1})\ \boldsymbol{X}\ \%\boldsymbol{Hvy}\ \boldsymbol{X}\ \boldsymbol{AADT})\boldsymbol{X}\mathbf{0.1}$$

$$= (\mathbf{4\ 157} + (\mathbf{3} - \mathbf{1})\boldsymbol{X}\ \mathbf{0.15}\boldsymbol{X}\mathbf{4\ 157})\boldsymbol{X}\mathbf{0.1}$$

$$= \mathbf{540}$$

The hourly volume can be expressed in terms of EVU/lane/day by multiplying the $EVU_{peak\ hour}$ with the traffic directional factor that expresses the volume in the primary direction in the peak hour. The typical directional factors are 60/40 for most roads (COTO, 2013).

Therefore, with regards to Bridge 5, carrying a typical paved road in flat terrain, the volume in the peak direction is:

540 X 60% = 324

The detour route has 2 paved lanes. According to Table 4, the capacity of the detour route is 1 000 EVU/lane/hour. The volume/capacity ratio for the detour route is therefore:

V/C= 540/1000 = 0.54

Applying the equation in Figure 3, for a V/C ratio of 0.54, the FIv/c = 92.3

Thus, **RCF = 92.3**

Step 4: Calculate the Riding Quality Factor (RQF)

The weighted average IRI for the links making up the detour route is 3. Applying the equation in Figure 4, for an IRI of 3, the FI_{IRI} = 75.9

Thus, **RQF = 75.9**

Step 5: Calculate the Road Safety Factor (RSF)

The detour route is a 6 m wide 2-lane paved road with 1 m paved shoulders. The verges along the road are accommodating and the curves on the road are flat. According to Section 4.2.4, the values to calculate FI_{PIA} are therefore as follows:

R_{base} = 34 for a surfaced single carriageway

$R_{intersection}$ = 30 (intersections at grade)

R_{Median} = 15 (no median)

f_c = 1 (curves are flat)

f_v= 0.80 (Accommodating verges)

f_l = 1.04 for lane width of 3 m (TMH 22, Table E-14)

f_s = 1.29 for a 1 m paved shoulder (TMH 22, Table E-14)

$PIA_R = (R_{base} + R_{intersections} + R_{median}) \times f_c \times f_v \times f_l \times f_s$

$= (34 + 30 + 15)\ ) \times 1 \times 0.8 \times 1.04 \times 1.29$

$= 84.8$

Reading from Table 5, for a paved 2-lane road with a flat topography, the PIA_{BASE} = 70

Therefore the ratio of PIA_R to PIA_{BASE} = 85/70 = 1.21

Applying the equation in Figure 5, the FI_{PIA} = 51.4

Thus, **RSF = 51.4**

Step 6: Calculate the User Risk Factor

In conformance to section 4.2.1, the User Risk Factor is taken as 50

Thus, **URF = 50**

Step 7: Calculate the BFI

Finally, the BFI for Bridge 5 is calculated by inserting the individual factor values into the BFI equation as follows:

$$BFI = 0.5 \times TVF + (0.08 \times DLF + 0.16 \times RCF + 0.16 \times RSF + 0.08 \times URF\ + 0.03 \times RQF)$$

$$BFI = 0.5 \times 80 + (0.08 \times 100 + 0.16 \times 92.3 + 0.16 \times 51.4 + 0.08 \times 50\ + 0.03 \times 75.9)$$

$$BFI = 40 + (8 + 14.8 \times 8.2 + 4\ + 2.3)$$

$$BFI = 40 + 37.3$$

$$BFI = 77.3$$

6. DISCUSSION OF RESULTS

The BFI equation, developed as part of this study, yielded the results presented in Table 8. The impact with regards to the individual factors has been calculated and is described in

Table 8. The BFI is a function of two main indicators, namely, the TVF for the bridge, based on the ADT value of the road over the bridge, and the FI_{Detour}. It is important to note is that a low TVF value implies severe loss of service should the bridge be unavailable for use, as high traffic volumes would have to use a detour. Also worth noting is that the lower the FI_{Detour} value is, the greater the chances that the detour is at a failed level of service. This implies that a bridge with a low BFI value should receive a higher priority with regards to maintenance compared with a bridge with a high BFI value. The unavailability of the bridge with the low BFI value would cause a major disruption for road users. The worst case is however the unavailability of bridges with no detour routes. Examples of such bridges are Bridge 2 and Bridge 7 in Table 8. Should these bridges be unavailable for use, major disruptions on the road would result, especially on bridges that accommodate high traffic volumes, because many trips would have to be aborted.

Table 8: Distribution of BFI Values for the 10 Sample Bridges

		Functional Index of Detour Route FI_{DETOUR}					
		0	**> 0-10**	**10-20**	**20-30**	**30-40**	**40-50**
TVF for Bridge		Detour route unavailable	Failed service levels	Poor service levels.	Moderate service levels.	Good service levels	Excellent service levels.
25	Catastrophic loss of service, between 1 000-5 000 ADT affected						
35	Moderate loss of service, between 5 000-10 000 ADT affected					Bridge 4	
40	Moderate loss of service, between 1 000-5 000 ADT affected	Bridge 7 Bridge 2		Bridge 1	Bridge 5 Bridge 3 Bridge 9	Bridge 8	
45	Minor loss of service, between 500 - 1 000 ADT affected				Bridge 6	Bridge 10	
50	Insignificant loss of service, less than 500 ADT affected						

7. CONCLUSION AND RECOMMENDATIONS

The study was primarily aimed at proposing a method to calculate functional indices for bridges based on the volume of the traffic carried by the bridge and the functionality of the detour route that would have to be used should the bridge have to be closed. The BFI was calculated by considering the effects on the user caused by a bridge that is unavailable for use and thus forcing the user to take a detour. The effects were measured in terms of traffic volume on the bridge and with regards to the detour route, indicators such as capacity, riding quality, user cost, and detour length were used.

The use of the multi-factor functional indicator presented in this study can be used in conjunction with condition indices when identifying and ranking bridges for maintenance purposes. In this way, it could contribute to preventing inconvenience to road users. Further research is recommended to develop weighting models considering all the indicators used to determine a combined bridge functional index.

8. REFERENCES

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