RISK-BASED LIFECYCLE ANALYSIS FOR ROAD STRUCTURES: THE BENEFIT OF AN IMPROVED RISK-BASED FUNDING ALLOCATION METHOD FOR MAINTENANCE AND REHABILITATION OF ROAD STRUCTURES UNDER BUDGET CONSTRAINTS

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ABSTRACT

With the current environment of slow economic growth in South Africa as well as the negative economic impact of the COVID-19 epidemic placing additional constraints on the national fiscus, resources made available for the management of the nation’s economic infrastructure are even more scarce, stressing the need for asset managers to optimally apply the limited available funding across asset portfolios.

While methods for allocating limited funding to competing infrastructure across a network of assets are highly developed for road pavements, current funding allocation methods defined in the TMH 22 for road structures are primarily based on direct assessments of condition and urgency from the field assessor and do not incorporate lifecycle performance, lifecycle cost, or any economic parameters in the prioritisation of expenditure on assets.

An alternative funding allocation method using a risk-based lifecycle analysis (RBLA) focused on achieving the optimal balance in asset performance, cost, and risk (driven by economic, environmental, and social factors) has been implemented by one of the largest metropolitan municipalities in South Africa.

This paper compares the projected impact of the two different funding allocation methods on the long-term performance of road structure asset portfolios using the municipality’s condition assessment data for general bridges. The comparison is made to investigate and quantify the benefits arising from adopting the RBLA method under resource constraints instead of the conventional TMH 22 method.

The RBLA resulted in insignificant changes in overall condition over a five-year assessment cycle but a notable reduction of risk of 24% when compared to the investment alternatives identified by the current TMH 22 method of prioritising structures. This indicates that under constrained funding levels, a higher return in terms of risk reduction benefits is possible for the same expenditure when implementing RBLA selected investment alternatives. It is, therefore, recommended that this method be considered by industry practitioners and further investigated and considered by COTO for improvement to current industry practices.

1. INTRODUCTION

1.1 Background

The current environment of slow economic growth in South Africa and the negative economic impact of the COVID-19 epidemic has placed additional constraints on the national fiscus. The fiscal constraints have reduced the resources made available to provinces and local government to manage the nation's economic infrastructure. This necessitates infrastructure asset managers to work more smartly with limited available funding in balancing the cost, performance, and risk of their infrastructure portfolios.

Funding for the planning of maintenance and rehabilitation of existing infrastructure is made available to provinces and local authorities through the Provincial Roads Maintenance Grant (PRMG) and the Rural Roads Asset Management Systems Grant (RRAMSG). The Committee of Transport Officials (COTO) has developed national guidelines for practitioners on how to plan and prioritise maintenance and rehabilitation using condition assessment information and lifecycle analysis methodologies (COTO, 2013). Methods for allocating limited funding to competing infrastructure across a network of assets are highly developed in the national guidelines for road pavements, which includes advanced methods that use optimisation algorithms to allocate funds using lifecycle performance, costs, and economic benefits.

However, the funding allocation methods defined in the TMH 22 for bridges and other structures are currently largely based on direct assessments of condition and urgency from the field assessor and do not incorporate lifecycle performance, lifecycle cost, or economic analyses. An Average Structure Condition Index (ASCI) and a Structure Priority Condition Index (SPCI), based on the condition assessment data, are respectively used to monitor trends and prioritise structures for maintenance (COTO, 2013; COTO, 2016). While the direct assessment method provides insight into repair needs, it does not provide insight into the consequences of not repairing those assets in need of repair but for which there is no funding available. While the TMH 22 makes provision for an improved method of prioritisation through a Combined Condition Index (CCI), which is a combination of the SPCI and a Functional Index (FI) that depicts how well the structure fulfils its functions, this index, at present, is neither well defined nor used by road authorities. Additionally, neither of the abovementioned methods consider the lifecycle performance, lifecycle costs, or any economic parameters in the prioritisation of which assets are to be repaired when and where under conditions of funding constraints. Furthermore, the current method of prioritisation does not allow any means of prioritisation of funding between different roadside structure types such as bridges, culverts, gantries, and retaining walls. Bridge repairs are typically viewed as more critical and receive priority in funding.

The notion exists that since bridges and other road structures deteriorate slowly and have different decay profiles to pavements, the concept of a-stitch-in-time-saves-nine is less relevant to structures. An argument is put forward that lifecycle and economic analyses, therefore, do not add sufficient value to the decision-making process. Identifying and prioritising repair needs at five-year interval inspections have been considered an appropriate management strategy.

An alternative funding allocation method using a risk-based lifecycle analysis (RBLA) that incorporates asset lifecycle performance, lifecycle cost, and economic parameters in the funding allocation process was implemented by one of the largest metropolitan municipalities in South Africa. This was done to achieve a better balance in asset performance, cost, and risk by optimising the allocation of constrained funding to repairs over time and across multiple road structure types.

This paper compares the projected impact of the two different funding allocation methods on the long-term performance of road structure asset portfolios using the municipality's reference dataset. The results show the benefit in funding efficiency that can be derived from using the RBLA method and makes a case for further development of this alternative method under conditions of constrained funding.

2. METHODOLOGY

A summary of the methodology used to compare the existing TMH 22 SPCI method and the alternative RBLA method is shown in Figure 1.

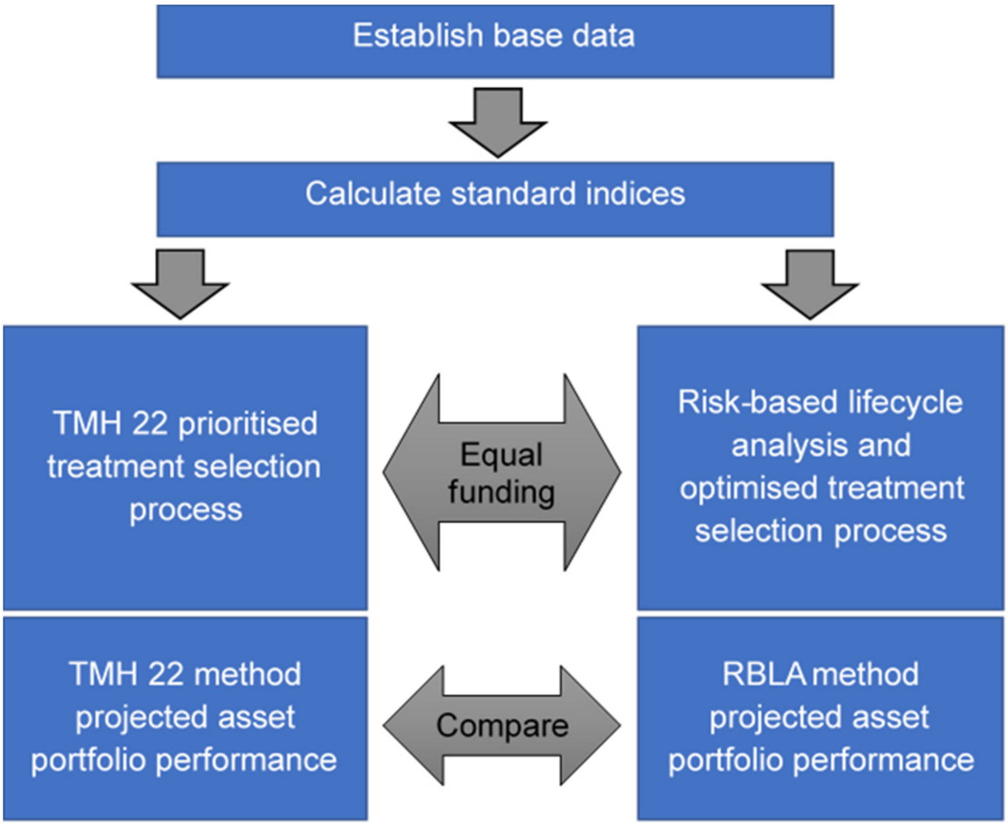

Figure 1: Schematic of the methodology

2.1 Establish Base Data

The metropolitan municipality manages a network of 10 452 km roads and 3 225 road structures. Of the 3 225 road structures, 2 675 structures were assessed in 2019 in accordance with TMH 19 visual assessment procedures. For the purposes of this paper, only general bridges are considered in the comparison. The 2019 visual assessments covered 496 general bridges.

2.2 Calculation of Standard Indices

As per the TMH 19, general bridges were inspected for visual defects at sub-item level (abutment 1, abutment 2, etc.) and rated according to a DER system, as described below (COTO, 2016):

D	Degree of defect:	The severity of the defect.
E	Extent of defect:	How widespread the defect is on the inspection item being inspected.
R	Relevancy of defect:	The consequence of the defect with regards to the structural or functional integrity of the inspection item or the safety of the user of the structure.

Condition indices are based on the assessed DER ratings of inspection sub-items (COTO, 2016).

2.3 Current TMH 22 SPCI Method

Following the current TMH 22 SPCI method of prioritisation, two indices were calculated, namely the ASCI and the SPCI. The ASCI is used to obtain an average overall condition and monitor trends. It can be used to give an indication of the effectiveness of the maintenance programme. The SPCI is a deduct system that is more sensitive to the influence of single very poor items on the overall condition of the structure and is used to rank structures in order of priority for maintenance, rehabilitation, and reconstruction activities. It is designed to identify structures with the greatest need for repair to be given the highest priority (COTO, 2013; COTO, 2016).

2.4 RBLA Method

The RBLA method analyses general bridges at a component level (i.e., foundation, substructure, superstructure, etc.). In addition to the calculation of the ASCI and SPCI, average condition indices of inspection items were converted to five condition states, ranging from very poor to very good, and aggregated to component level by grouping items with similar behavioural properties. Condition deterioration and risk models were used to forecast the change in asset condition and asset risk exposure for each asset over time.

2.5 Treatment Selection Process

A technical needs analysis was initially carried out on the general bridges assessed to identify the immediate maintenance requirements for each bridge. Based on the maintenance needs identified, projects were ranked according to the SPCI to represent the TMH 22 SPCI prioritisation process. Based on the TMH 22 SPCI method, the priority list does not change over time and is essentially a snapshot of condition that is used for budgeting and spending purposes over a period of five years until the next round of assessments are conducted, and a new snapshot is obtained. Condition deterioration/ prediction is not considered in the prioritisation process.

The RBLA method selects the maintenance projects providing the highest reduction in risk over the entire network of bridges. Condition deterioration/prediction is modelled using Markov chain deterioration models.

Two risk-based lifecycle analyses were carried out in dTIMS (Deighton Total Infrastructure Management System – an international commercial software package) to compare the impacts of investment alternatives, as determined by the TMH 22 SPCI method and the RBLA method, on the predicted infrastructure asset condition and monetary risk for the next five years for a constrained annual funding level of R30 million. The funding level is less than what is ideally needed based on the lifecycle analysis, but is more than the current budget for bridges. For the purposes of the comparison, the resultant condition and risk impact were quantified using the RBLA models for both funding allocation methods. The only variable in the comparison is the method of treatment selection within the constrained budget. A summary of the TMH 22 SPCI and RBLA methods being compared is provided in Table 1.

Table 1: Comparison between SPCI and RBLA methods

	TMH 22 SPCI Method	**RBLA Method**
Data analysis	ASCI & SPCI	ASCI, SPCI & condition state values
Prioritisation	SPCI ratings	Business risk exposure
Condition deterioration	None	Markov model

3. RBLA MODEL

Models used for the deterioration modelling of infrastructure assets are broadly classified as either deterministic or stochastic. Deterministic models are based on observed trends or theoretical and experimental analyses of infrastructure asset behaviour. Stochastic models, based on statistical theory, are primarily used when there is a lack of mechanistic models that reflect the infrastructure decay or the decay trends. A risk-based lifecycle analysis incorporates a stochastic model, allowing for the integration of probabilities and uncertainties in infrastructure asset behaviour into the decision process.

3.1 Data Management Approaches

The TMH 19 surveyed condition data can be analysed at an element level (i.e., inspection items such as piers, abutments, etc.), component level (i.e., foundation, substructure, superstructure, etc.), or structure level.

Road structures, such as general bridges, consisting of many elements, are analysed at a component level, at which element level average condition indices are aggregated to component level using element groupings, based on similar behavioural properties. Road structures consisting of fewer elements, are analysed at a structure level, at which all element level average condition indices are aggregated together.

To process element level data to structure / structural component level data, element level average condition indices are converted to five condition states ranging from very poor to very good. TMH 22 proposed inspection item ASCI weight sets are then used together with the element level condition states to determine the percentage of the structure or structural component per condition state.

3.2 RBLA Model Definition

The risk of a structure is defined as the possibility of a structure experiencing a condition failure and is a function of the probability of failure and consequence of failure, as expressed in Equation 1 (COTO, 2013).

$$Risk = PoF \times CoF \qquad (1)$$

Where:

PoF = Probability of condition failure of a structure
CoF = Consequence of condition failure of a structure

3.3 Probability of Failure

Condition failure occurs when a structure or structural component has deteriorated to a very poor condition state. The probability of failure of a structure is defined in Equation 2.

$$PoF = 1 - \left[\left(1 - P_{VP_1}\right)\left(1 - P_{VP_2}\right)\left(1 - P_{VP_3}\right) \ldots \left(1 - P_{VP_n}\right)\right] \qquad (2)$$

Where:

P_{VP_n} = Percentage of n[th] structural component in very poor condition; where a structure is not analysed at component level, P_{VP} (n=1) refers to the percentage of the structure in very poor condition

The probability of a structure or structural component presenting with a very poor condition state is dependent on the current condition of the structure, the rate of deterioration as defined by Markov chain modelling parameters, and the defined maintenance strategies.

3.4 Markov Chain Deterioration Model

A Markov chain model defines the transition of one state to another. With regards to the RBLA, Markov chain modelling is used to define the transition of a structure or structural component from its current condition state to a worse condition state. The probability of a structure or structural component transitioning from its current condition state to a worse condition state is known as transition probability. The transition probability, defined by the transition probability matrix (TPM), defines the predicted annual deterioration rate of a structure or structural component and is derived from the estimated useful life of the structure or structural component. The annual condition is calculated using Equation 3 (Van As, 2008).

$$P_n = P_{n-1} \cdot P^n \qquad (3)$$

Where:

P_n	=	Condition state vector in year n, stating the % of the structure / structural component per condition state
P_{n-1}	=	Condition state vector in previous year after maintenance
P	=	Transition probability matrix (TPM)
n	=	year n

3.5 Maintenance Strategies

The predicted condition and the initial SPCI are considered in maintenance treatment triggers. The condition state vector of the structure / structural component(s) is reset depending on the treatment applied.

3.6 Consequence of Failure

The consequence of failure model is a triple bottom line model in which the impact of a condition failure on user (travel delays and additional vehicle operating costs), environmental (CO_2 emissions due to congestion), health and safety (injuries and fatalities), and social (legal factors related to injuries and fatalities) factors is identified and expressed in monetary terms.

The cost of consequence varies for each structure and is influenced by the following parameters:

- Structure type.
- Bridge/culvert type, i.e., vehicular, railway, pedestrian.
- Type of infrastructure or land over which a general bridge crosses, i.e., roadway, railway, waterway, agricultural land.
- Overall structure length and width/height.
- Road class.
- Average annual daily traffic (AADT) and traffic composition.
- Population in close proximity to the structure.
- Reconstruction cost.

3.7 Risk-Based Optimisation

The concept behind the RBLA is to minimize the risk over the lifecycle of the structural network under the given budget constraints (IIMM, 2015). A set of possible maintenance strategies are triggered for the structural network over the analysis period. The annual risk associated with each maintenance strategy, as well as the resulting savings in risk between the Do-Nothing and maintenance strategy, are determined. The annual savings in risk are cumulated over the analysis period and used to determine the most efficient maintenance strategy from a risk reduction point of view. This concept is illustrated in Figure 2 and Equation 4. The benefit (savings in risk) is the area under the curve between the risk resulting from the Do-Nothing and maintenance strategies. The analysis seeks to maximise the benefit, given than each asset's risk profile and cost to repair is different.

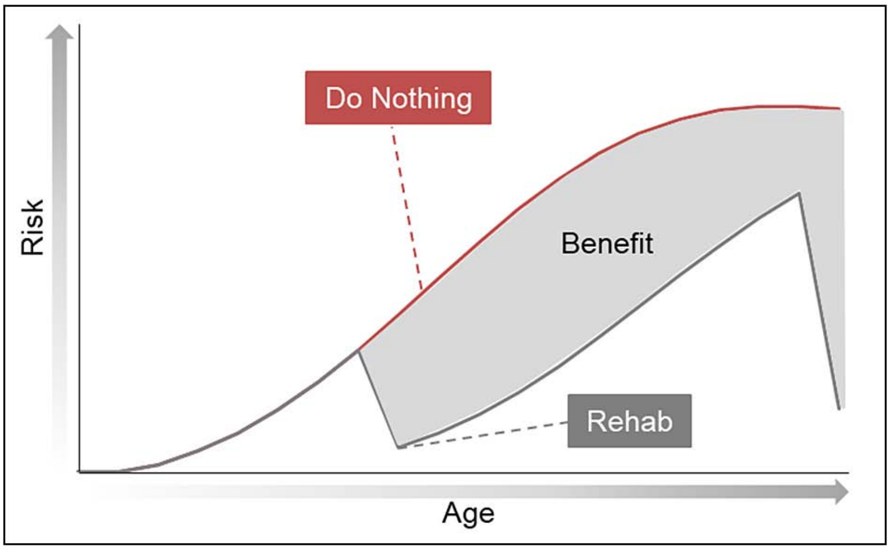

Figure 2: Risk-Based Optimisation

$$Benefit = \sum_{i=1}^{i=n} \left(Risk_{DN_i} - Risk_{Repair_i}\right) \rightarrow Max \quad (1)$$

Where:

$Risk_{DN_i}$ = Risk resulting from Do-Nothing strategy in year i of analysis period

$Risk_{Repair_i}$= Risk resulting from maintenance strategy in year i of analysis period

Figure 3 illustrates the interaction amongst the RBLA model components.

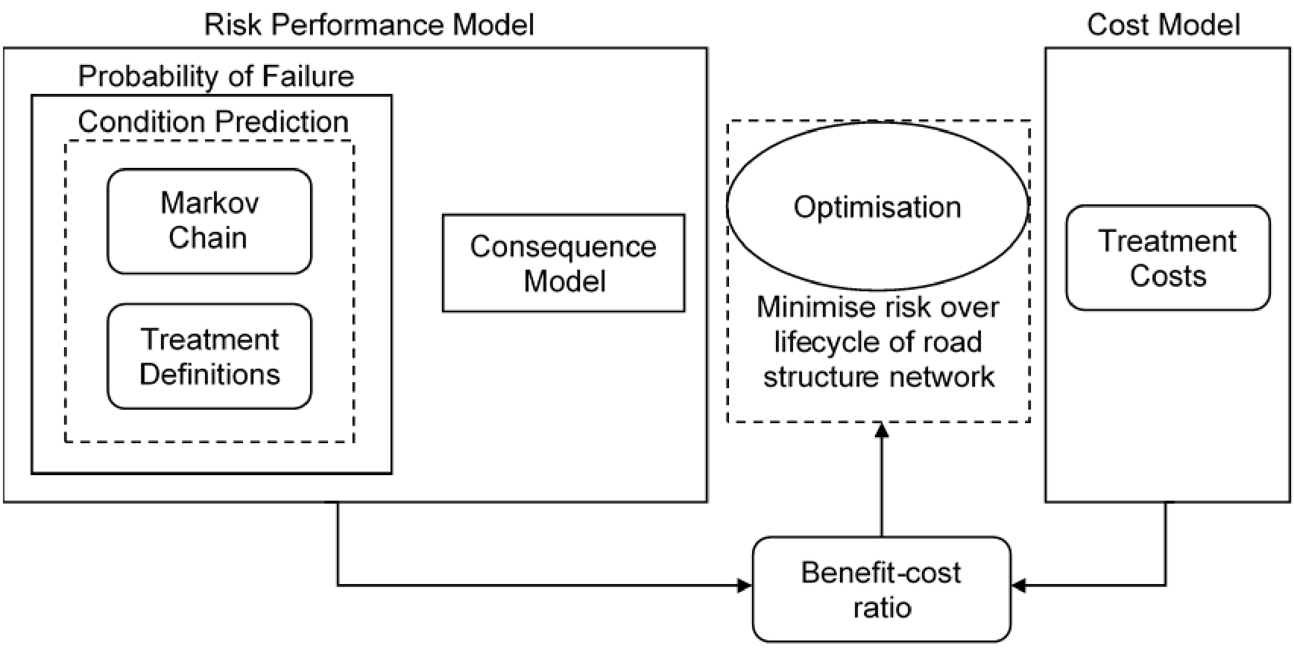

Figure 3: Interaction amongst RBLA model components

4. FINDINGS

4.1 Predicted Condition

The impact of the TMH 22 SPCI and RBLA funding allocation methods on the predicted ASCI over a five-year assessment cycle is presented in Figure 4. Both methods yield a similar overall condition over time, with the TMH 22 and RBLA methods respectively presenting with 82% and 83% in the final year.

The TMH 22 SPCI method currently used by industry practitioners, prioritises treatments solely on the assessed condition of the general bridges, effectively treating bridges in a worse condition first, where funding allows. The subsequent work programme is not optimised to consider the long-term condition of the entire network of general bridges. A larger portion of the budget is, therefore, allocated towards a smaller number of bridges, which are more costly to maintain with many bridge repairs being deferred.

The RBLA method selects the maintenance alternatives providing the greatest benefit (minimal risk, driven by condition) over the entire analysis period for the entire network of bridges, for the funds expended. This is achieved by allocating the constrained funding to as many high-risk bridges as possible, sometimes treating bridge components that are less costly to maintain.

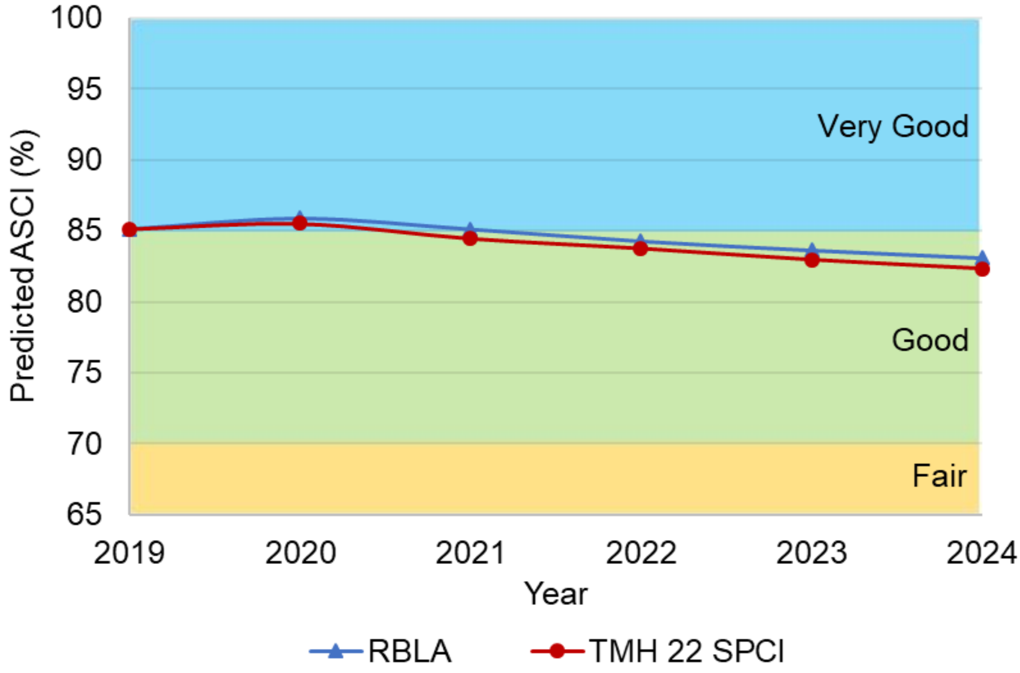

Figure 4: TMH 22 SPCI vs RBLA predicted impact on condition

4.2 Predicted Risk

The impact of the TMH 22 SPCI and RBLA funding allocation methods on the predicted risk exposure over a five-year assessment cycle is presented in Figure 5. The RBLA method, which aims to minimise the risk over the bridge network's lifecycle under the given budget constraints, results in a reduction of risk in each year with a maximum of R55 billion (24%) lower risk in the final year.

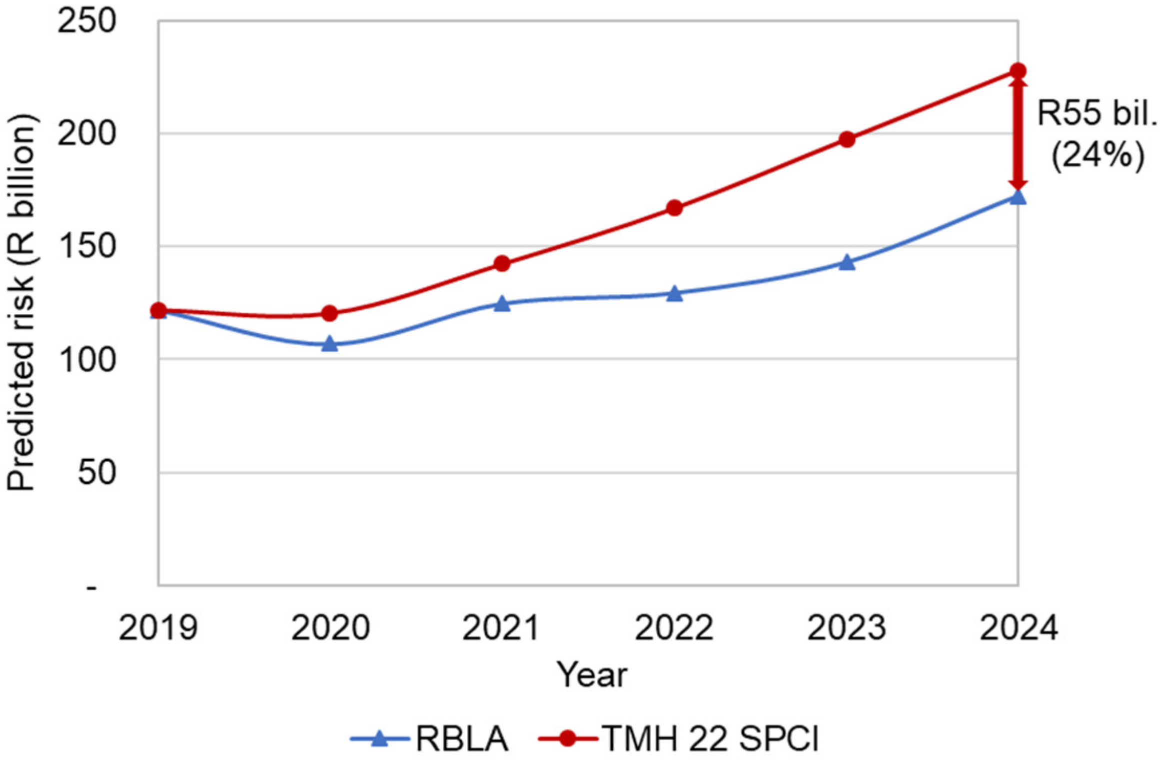

Figure 5: TMH 22 SPCI vs RBLA predicted impact on monetary risk

Under constrained funding levels, where the needs of all structures cannot be addressed, allocating funds to treat structures with higher risk-benefit / cost ratios provides a greater overall benefit in lower risk for the funds expended. With the same amount of funding, the risk associated with user, environmental, health and safety, and social consequences can be minimised to a greater extent than when using the TMH 22 method.

5. CONCLUSIONS

The projected impact on the long-term performance of road structure asset portfolios of an alternative risk-based lifecycle analysis (RBLA) and funding allocation method was compared to that of the current TMH 22 SPCI method for prioritising the maintenance and rehabilitation of road structures. Implementing an RBLA method on general bridges maintained by one of South Africa's largest metropolitan municipalities resulted in similar overall condition over time but a notable reduction in risk exposure of 24% when compared to the investment alternatives identified by the current TMH 22 SPCI method of prioritising structures.

There is a significant benefit to implementing an RBLA approach under conditions of funding constraints, as this method ensures that available funding is allocated in a manner that more effectively reduces the user, environmental, health and safety, and social consequences of asset performance over time than current conventional methods.

The RBLA approach quantities risk in a monetary value which allows the calculation of return on investment for maintenance projects and furthermore can be extended to optimise expenditure across different infrastructure asset types. It is recommended that this method be considered by industry practitioners and further investigated and considered by COTO for improvement to current industry practices.

6. REFERENCES

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