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Developing Key Performance Indicators for the Assessment of Existing Bridges

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ABSTRACT: The operators of transport infrastructure are to maintain the functionality of the bridges in their care with limited funds. The necessary prioritization is aided significantly by Key Performance Indicators such as reliability, safety and availability, which should consider all available information on the bridge provided e.g. by visual inspection, non-destructive testing, structural health monitoring and computational methods. A framework to develop such KPIs for Germany is outlined in the present paper.

1. INTRODUCTION

Highway authorities worldwide are responsible for the management of vast road networks with numerous bridges. While traffic numbers and loads continuously keep growing, the condition of the existing structures is increasingly deteriorating. In general, the authorities have only limited funds at their disposal to maintain the functionality of the crucial transport infrastructure. Consequently, they are faced with the difficult task of prioritizing investments in bridge repairs and replacements based on the limited information at their disposal. These decisions are commonly made based on the condition of the structure as observed for example in bridge inspections carried out in regular intervals. Meanwhile in some cases several additional Performance Indicators (PIs) for bridges may have emerged, such as reassessment results, monitoring data, results of non-destructive testing etc. which may shed additional light onto a structure's condition and influence its level of urgency regarding replacement or strengthening. While there have been investigations into the influence of monitoring or materials testing onto the reliability of a specific structure, these methods typically require extensive modelling and expert knowledge. Although these methods are effective at the level of a selected bridge, they cannot be applied on the transport infrastructure as a whole in order to facilitate the prioritization of investments. This paper investigates an approach where different indicators of structural performance are linked and weighted in order to generate a few Key Performance Indicators (KPIs) which then may serve as the basis for the prioritization of funds.

2. KEY PERFORMANCE INDICATORS

Before going any further, we need to define Performance Indicators in general and establish differences of Key Performance Indicators. According to the fib Model Code 2010 a Performance Indicator is "a measurable/testable parameter (i. e. characteristic of materials and structures) that quantitatively describes a performance aspect" (fib 2013). The term Key Performance Indicator was originally coined by economists to "represent a set of measures focusing on those aspects of organizational performance that are the most critical for the current and future success of the organization" (Parmenter 2007). There is extensive literature on the topic of identifying those PIs which may be regarded as KPIs, but commonly it is required that they fulfill the SMART criteria introduced by Doran (1981). This acronym stands for:

- Specific,
- Measurable,
- Assignable,
- Realistic and
- Time-related.

This concept can also be transferred to asset management. In essence a KPI is a quantitative parameter, with a suitable scale, describing a well-defined, meaningful aspect of a structure's performance as a function of time.

Almost every country has developed PIs for the assessment of structures. Within the framework of COST Action TU 1406, Working Group 1 has compiled a database of these PIs for more than 30, mainly European, countries (Strauss et al. 2016). This database has been extensively analyzed and the collected PIs had been grouped according to various criteria with the objective to define a common group of quality specifications that can be assumed by all these countries, with the aim to manage the existing roadway infrastructure from a European and not only a country-specific perspective. The similarities between the countries are apparent in Figure 1, where for each preselected KPI the number of appearances in the national documents is counted.

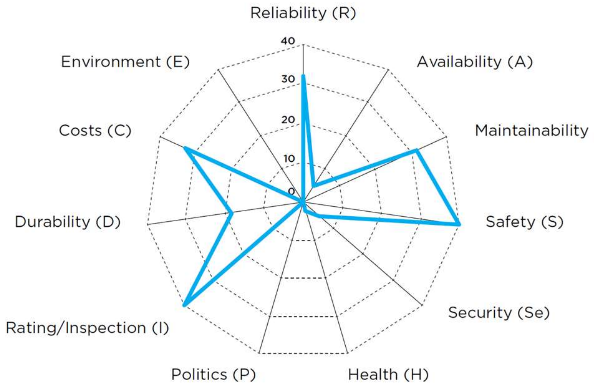

Figure 1: Number of PIs related to the pre-defined KPIs based on the categorized, homogenized and reduced PIs of the findings from the screening and processing of the national applied documents (Strauss et al. 2016).

It was concluded that no clear distinction between PIs and KPIs can be identified. Nevertheless, the partners included in the COST Action TU 1406 agreed upon the following five KPIs (Hajdin et al. 2018):

- Reliability is the probability that a bridge will be fit for purpose during its service life. It is the complement to the probability of structural failure (safety), operational failure (serviceability) or any other failure mode.
- Availability is the proportion of time a bridge is open for service. It does not include failure-related service outages but the ones due to planned maintenance interventions. Alternatively, the Availability can be measured as additional travel time due to an imposed traffic regime on bridge.
- Safety is the situation of life and limb being protected from harm during the service life of a bridge. Loss of life and limb due to structural failure is not included by this definition (since it would overlap with the Reliability).
- Economy is related to minimizing the long-term cost of maintenance activities over the service life of a bridge. Herein the user costs incurred due to detours and delays are not included.
- Environment is related to minimizing the harm to environment during the service life of a bridge.

While the identification of these five shared KPIs is an essential step forward towards a shared European perspective, in order for KPIs to become an effective tool in asset management, it is essential to also make them measurable. Ideally the KPIs should be defined in a way which is adjusted to the established practices how a respective country gathers information on its structures. If this aspect is not considered adequately, even a KPI with a flawless theoretical background is of no practical use. If the absence of data inhibits the calculation of its value for the assets that are to be managed, it cannot serve as a valuable tool for asset management. Within the framework of a research project, which is coordinated and overseen by the German Federal Highway Research Institute, the Austrian Institute of Technology is commissioned, to develop and analyze such suitable KPIs for the German highway network.

3. METHODS OF CONDITION ASSESSMENT

The operators of transport infrastructure have a variety of methods at their disposal to assess the condition of the structures in their care. In addition to the results of the structural inspection, which in Germany are usually collected at intervals of six (main inspection) or three (simple inspection) years, non-destructive testing methods or structural health monitoring can be used to gain further information. Furthermore, reassessments have been carried out for numerous structures based on the Reassessment Guideline for Existing Bridges (BMVBS 2011). The individual characteristics of the information collected by these different methods are described in the following sections.

3.1. Visual inspection of structures

The basis for the condition assessment of structures in Germany is the visual inspection according to DIN 1076 (1999). This standard provides definitions and lays the foundations for the inspection of structures. Comprehensive specifications on the uniform collection, assessment, recording and evaluation of the results of structural inspections are contained in RI-EBW-PRÜF (BMVI 2017). The implementation of this guideline enables the use of a standardized software, which also provides examples as a support for the damage assessment and thus facilitates a simple and uniform evaluation of the inspection results. The nationwide, uniform damage assessment is further promoted by the fact that only persons who have obtained a certification by attending one-week training courses are permitted to be commissioned with inspection services. The guideline defines the performance indicators "structural safety", "traffic safety" and "durability". Five levels of damage assessment from 0 to 4 are described for each of these three aspects. Damage is recorded separately for the individual components of the bridge. The overall condition grade for the structure is determined from the damage assessments in accordance with the algorithm according to Haardt (1999). The condition grades determined in this way enable a holistic assessment of the condition of structures in the German road network.

If the regular visual inspections reveal complex damage patterns, additional detailed information on the type and extent of the defects must be collected by conducting a so-called “assessment on object level” (Krieger et al. 2000). The influence of the observed defects on the structural safety and durability must be determined, considering the anticipated remaining service life.

3.2. Non-destructive testing

Such an assessment on object level is often accompanied by non-destructive testing of the affected bridge components. Non-destructive testing methods are becoming increasingly important in the condition assessment of structures. Due to the constant technological development, the range of possibilities for gaining additional information about the structure is growing continuously. In the ZfPBau compendium of BAM (Schickert et al. 1991) already 84 different devices or methods for non-destructive testing in the construction industry were listed. In the module "Non-destructive testing methods" of the German Centre for Rail Traffic Research 22 testing methods for steel, 26 testing methods for concrete and 14 testing methods for masonry structures are described in detail (DZSF 2021). Of course, not all of these methods are suitable for road bridges, some can only be carried out on small test specimens in the laboratory, others may only be used for certain materials and still others are uneconomical for bridges with commonly large, difficult-to-access components. Several methods however, like rebound hammer test, infrared-thermography, potential mapping, radar, impact-echo, ultrasound or eddy current testing have already been successfully applied to road bridges (Holst et al. 2006, Friese et al. 2009, Diersch et al. 2015).

3.3. Structural health monitoring

Monitoring can be regarded as a special case of non-destructive testing since sensors are used to determine the properties of the structure without impairing it. The essential characteristic of monitoring is that the development of certain parameters over time is observed. Basically, two types of monitoring can be distinguished (Haardt and Holst 2017): On the one hand, monitoring can serve to improve or calibrate a finite element model by comparing calculated predictions with measurements on the structure. The second possibility is that monitoring is based on data patterns, mostly by analyzing deviations from an initial state. Monitoring can involve measuring and recording a wide variety of bridge properties, e.g. sensors can be used to capture the following parameters (Schnellenbach-Held et al. 2014):

- mechanical parameters:
    - strain, displacement, inclination,
    - vibrations,
    - stresses,
    - forces, prestressing forces,
- physical parameters:
    - temperature and humidity,
- chemical parameters:
    - corrosion,
- parameters of actions:
    - vehicle information (weight, speed, etc.),
    - wind speed, wind pressure,
    - air temperature and humidity.

An essential goal of structural health monitoring is to increase the reliability of structures with deficits as a compensatory measure. However, quantifying the influence of permanent monitoring on the operational reliability of existing bridges often requires complex considerations (Ralbovsky et al. 2020).

3.4. Computational methods

In the past decades, computational methods have become increasingly important in the reassessment of existing bridges, especially since the compilation of list with a total of more than 2000 structures in Germany, which are to be investigated as a matter of priority, as well as the introduction of the Reassessment Guideline for Existing Road Bridges (BMVBS 2011). The results of these recalculations have significantly increased our knowledge of the condition of existing bridges.

In 2020 the German Federal Ministry of Transport and Digital Infrastructure introduced the load-bearing index as an additional independent parameter for the structural assessment of bridges. Even if the load-bearing index is currently mostly calculated automatically based on some parameters of the bridge, the aim is to validate or refine it by a reassessment, especially in cases where an insufficient load-bearing capacity is indicated.

The reliability of existing bridges is also subject of intensive research efforts internationally. The fib Bulletin 80 (2016) describes various methods of performing calculations for existing structures with the help of adjusted partial safety factors that take into account additional information on the structure, e.g. from the results of material tests or the monitoring of actions. Based on these principles, the Task Group 1.3 of the International Association for Bridge and Structural Engineering (IABSE) has set itself the goal of developing methods for the calibration of adjusted partial safety factors for existing bridges (Boros et al., 2021, Orcesi et al., 2021).

4. DEVELOPMENT OF KPIS FOR GERMANY

Having described the heterogenous sources and types of data the German operators of transport infrastructure have at their disposal, we may now focus our attention on the methods which enable a synthesis of this patchwork of information. The current research project aims to investigate three KPIs in particular: reliability, safety and availability. They shall be addressed successively in the following sections.

4.1. Reliability

Regarding the reliability of the bridge two main aspects need to be considered: the computed load bearing capacity of the bridge and the observed structural condition. This is also in line with the two key performance indicators that are currently used in Germany, namely the load-bearing index and the condition grades. However, since these two indicators fail to consider several sources of information on the structure, it is intended to develop more advanced key performance indicators for both aspects, which allow a more precise assessment.

4.1.1. Computed load-bearing capacity

For the computed load-bearing capacity, the load factor κ_i defined in the Reassessment Guideline (BMVBS 2011) offers a good starting point:

$$\kappa_i = E_{d,i,LM}/R_{d,i} \tag{1}$$

The load factor is defined for each limit state as the ratio between the respective internal forces due to the actions of the defined targeted load model and the resistance of the structure. If actions with minor influence for bridges such as wind and temperature are neglected, equation (1) may be rephrased as:

$$\kappa_i = \frac{Q_{k,i,LM}}{R_{k,i}}\left(\gamma_{Gd}\gamma_g\frac{G}{Q} + \gamma_{Qd}\gamma_q\right)(\gamma_{Rd}\gamma_m) \tag{2}$$

where:

$Q_{k,i,LM}$ is the characteristic action due to the targeted traffic load model;

$R_{k,i}$ is characteristic value of the resistance;

γ_{Gd} is the partial factor accounting for model uncertainty in self weight;

γ_g is the partial factor accounting for variability of self-weight;

$\frac{G}{Q}$ is the ratio of self-weight and traffic load;

γ_{Qd} is the partial factor accounting for model uncertainty in traffic loads;

γ_q is the partial factor accounting for variability of traffic loads;

γ_{Rd} is the partial factor accounting for model uncertainties in the resisting model;

γ_m is the partial factor for material properties.

Describing the load factor with equation (2) offers various possibilities to introduce the effect of additional information available on the structure. For example, the results of non-destructive tests allow not only the adjustment of the characteristic value of the resistance $R_{k,i}$, but also of the partial factor for material properties γ_m due to the observed coefficients of variation. In case of a weight limit $Q_{k,i,LM}$ may be reduced, if it is paired with the measurements of a Weigh-in-Motion system, also the partial safety factor γ_q can be updated. Structural health monitoring combined with load tests can be used to calibrate computation models and modify the partial factors accounting for model uncertainties γ_{Gd}, γ_{Qd} and γ_{Rd}. Ideally the basic value for κ_i is provided be the reassessment based on the Reassessment Guideline (BMVBS 2011), but where this is not available a classification based on essential parameters such as year of construction, span, type of structure, presence of prestressing steel susceptible to hydrogen induced stress corrosion cracking, etc. can be carried out in analogy to the load-bearing index.

4.1.2. Observed structural condition

The results of the regular visual inspections provide a valuable insight into the actual condition of the bridge. Yet, the algorithm used to determine the overall condition grade of the bridge is not suitable to provide a KPI for reliability, since other aspects such as traffic safety and durability are also included (Haardt 1999). The existing ratings for the individual components can however be used to derive a suitable KPI for reliability. The defects observed at different component groups should however be weighted, since damages of the parapets must be assigned a different significance than those of the prestressing or suspension cables. The additional information provided by structural health monitoring must also be addressed here. If for example existing cracks are constantly monitored without showing any adverse changes, a better grade may be assigned than in the absence of such measures.

4.1.3. Aggregated reliability assessment

Eventually the computed load-bearing capacity and the observed structural condition have to be combined into a unified KPI of reliability. High reliabilities require that both the load-bearing capacity is fulfilled, and no relevant damage is observed. If any of these requirements is not met, the reliability is impaired. In structures with high reliability, hardly any damage is to be expected, therefore a differentiation can be made here primarily based of the load-bearing capacity. For structures with low reliability, the observed structural condition becomes increasingly important. This fundamental relationship is illustrated in Figure 2.

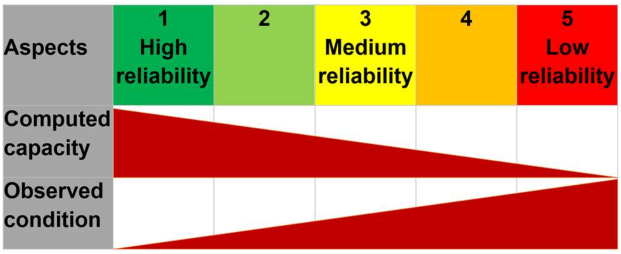

Figure 2: Aggregated assessment of the reliability

It is important to realize, that in the case of limit states with brittle failure, the time interval, in which damage can be detected, may be too short to take countermeasures, and therefore here the computed load-bearing capacity is paramount.

4.2. Safety

The second key KPI in the assessment of structures, besides reliability, is safety, i.e. the avoidance of dangers to human life. It is important to note, that the loss of human life due to structural failure is not included here. The assessment can be made based the observed condition of the bridge. The damage assessments carried out during the regular visual inspection for traffic safety provide the required data, which can be further analyzed. Here too, further information on the bridge may be included in the assessment. An important factor could be the average daily traffic observed on the bridge, which is also stored in the software used by the highway administrations. The presence of a traffic management or de-icing system could also be taken into account.

4.3. Availability

A strong interrelation between the reliability, safety and availability of a structure exists. After all, the availability of the structure is only given if a required minimum level of both reliability and safety can be guaranteed. In addition, the duration of maintenance or upgrading measures must be considered. Restrictions in availability can also occur, e.g. in the form of weight limits or temporary closure of lanes for repairs. A suitable way to take this into account would be to determine the availability as an integral over the life of the structure. This interrelation between reliability, safety and availability is displayed in Figure 3 for a fictional example.

Availability plays a special role in the KPIs for bridges. On the one hand, as described above, it is dependent on the other two essential KPIs reliability and safety. Precisely because of this, it is perhaps the most meaningful KPI, since the importance of reliability and safety primarily stems from the fact that these are the prerequisites for the availability of the bridge in the long term. In addition, it should be noted that this KPI, unlike the other two, can be determined objectively in retrospect. For each bridge the actual service life between the time of construction and decommissioning is measurable (if necessary, corrections can be made in the case of temporarily limited availability, as described above). In contrast, an objective evaluation of reliability or safety would require a statistical analysis of very rare events, which are impossible to conduct since every bridge may be considered a prototype.

This makes this indicator particularly suitable for a systematic review and subsequent recalibration of the developed KPIs and forecasting models. The algorithms developed and continuously refined in this manner can provide a foundation for the life cycle management of existing bridges. Different maintenance strategies can be cross-examined and compared with each other. For example, does it make more sense to carry out smaller maintenance measures at shorter intervals or is it better to bundle them into a few larger interventions?

5. FORECASTING

The initial definition of KPIs may be carried out based on previous experience and expert knowledge. The results of such a prioritization may be compared to the actual choices made hitherto, especially where historic data is available like in the case of the ratings of visual inspections. The developed algorithms can furthermore be used for forecasts on the future development of the investigated KPIs. The observed differences will indicate that some choices should be reinvestigated, and in many cases the definition of the KPI needs to be adjusted. By this procedure, possibly with the use of algorithms based on artificial intelligence (e.g. clustering algorithms, random forest analysis, support vector machines, neural networks), the definition of the KPIs may be improved gradually with time, as an increasing amount of data becomes available.

6. CONCLUSIONS

In essence, in the course of the research project, methods will be developed, according to the outlined concepts, to summarize all the information available on the bridge into a few key performance indicators, namely reliability, safety and availability. As a result, highway authorities may obtain a valuable tool, which on the long run could provide an increasingly accurate assistance in the optimal allocation of scarce funds.

7. OUTLOOK

It has to be noted, that the present study solely focuses on three out of the five shared European KPIs identified, neglecting so far economy and environment. While the aspect of economy may be quantified comparatively clearly by estimating the costs of different actions, environmental considerations were hitherto more difficult to grasp. The recent introduction of Environmental Product Declarations and their increasing numbers have however paved the way for a more comprehensible assessment of environmental aspects, which is currently the focus of further research on the subject at the AIT.

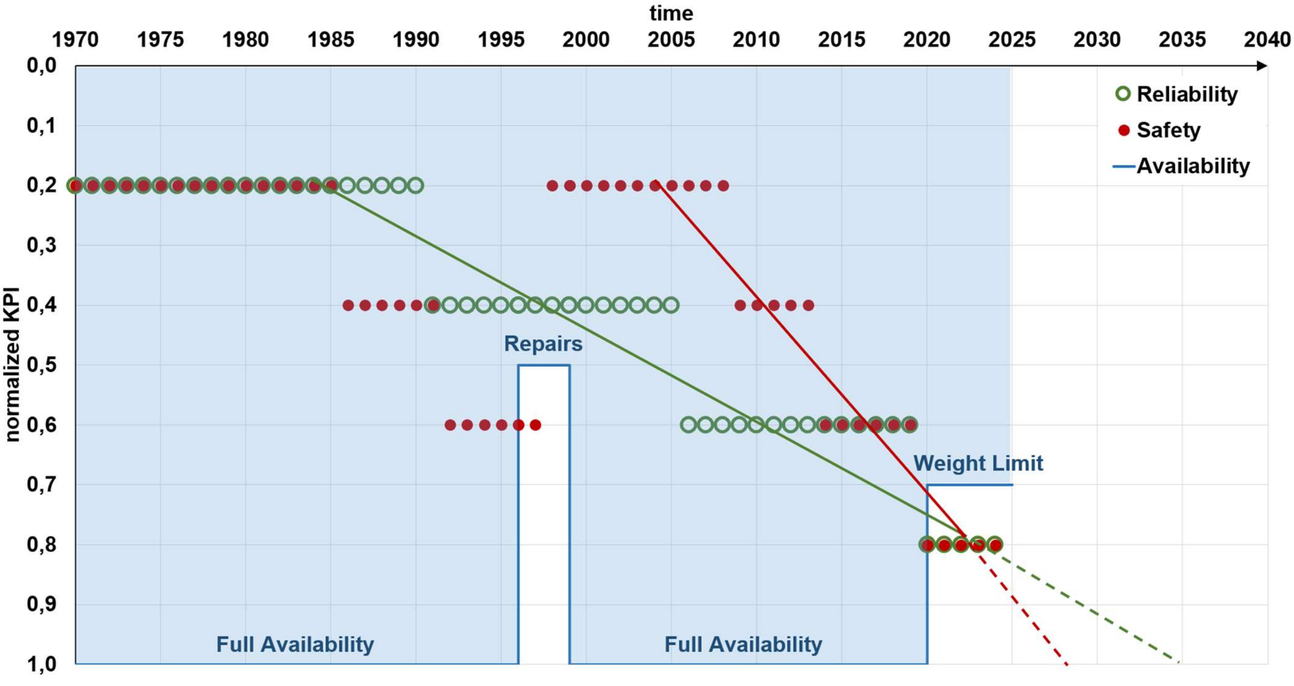

Figure 3: Interrelation between Reliability, Safety and Availability

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