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Use of Monitoring for Highway Bridges on Federal Highways in Germany – Current Status and Future Development

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ABSTRACT: The use of monitoring for bridges on federal highways is currently not widespread. Monitoring is primarily used when damage is already present or when deficits resulting from the recalculation or which occur due to the design. The potential of monitoring to support maintenance towards a predictive lifecycle management approach is not being fully utilized.

As part of the exchange with the structure managers in Germany and a literature search, it has been shown that the challenges lie in the lack of standardization, insufficient expertise, and missing fundamental principles. To address these challenges, various research projects have been planned and carried out. These include the “Documentation on Monitoring of Bridge Structures,” the “Guideline – Strategic Use of Monitoring for Civil Engineering Structures,” the “Birth Certificate for Bridge Structures,” and the project on “Standardized Data Models.”

This article aims to present the challenges and initial solution approaches from these projects. The goal is to illustrate support options for the increased and targeted use of monitoring in bridge structures on Germany’s federal highways. Additionally, the article provides a classification of these challenges within the European context.

KEY WORDS: monitoring, road bridge, standardization

1 INTRODUCTION

The bridges on federal highways face a variety of challenges. The main causes include the significant increase in traffic, especially in freight transport, the advanced age of the bridges, and a backlog of maintenance measures. Monitoring offers a way to address these challenges. It can be used effectively to ensure availability by detecting, assessing, and tracking safety reserves, changes, and weaknesses, thereby enabling predictions of future behavior. Additionally, monitoring allows for the recording of actual loads and impacts.

The data obtained through monitoring can support and optimize maintenance management, as it enables a more precise assessment of the current condition and better forecasting of condition changes. This, in turn, helps gain valuable time for necessary repair measures or replacement constructions.

However, the full potential of monitoring has not yet been realized. This article discusses the use of monitoring in Germany, as well as challenges in Europe, and particularly Germany. It serves as a foundation for identifying necessary developments and projects that can promote a more extensive and targeted application of monitoring.

2 MONITORING – CURRENT STATUS

2.1 General

Monitoring refers to the overall process of recording, analyzing, and evaluating structural responses and/or impact factors using a measurement system over a representative period. This includes tracking the temporal development of the measured variable through continuous, periodic, or event-based measurements, both on a global and local scale [1].

The effective use of monitoring encompasses the entire process, from the "definition of the research question" to the "evaluation." This process ensures that monitoring contributes to answering open questions related to a structure. [1; 2].

The goal of monitoring is to obtain additional information about the condition of the structure. This information serves as a basis for describing the current state and deriving forecasts for future behavior. The results can then be used to make maintenance decisions on a more informed basis.

2.2 Current use of monitoring

A survey conducted by the Federal Ministry of Transport in 2020 revealed that the use of monitoring for bridges on federal highways is limited to existing damage and deficits. The 100 monitoring measures identified in the survey primarily focused on bridges built between 1960 and 1980 and reflected the typical distribution of bridge types on federal highways, with a particular emphasis on prestressed concrete bridges (Figure 1 and Figure 2). The monitoring measures were mostly carried out to capture the structural response using deformation and temperature sensors [3].

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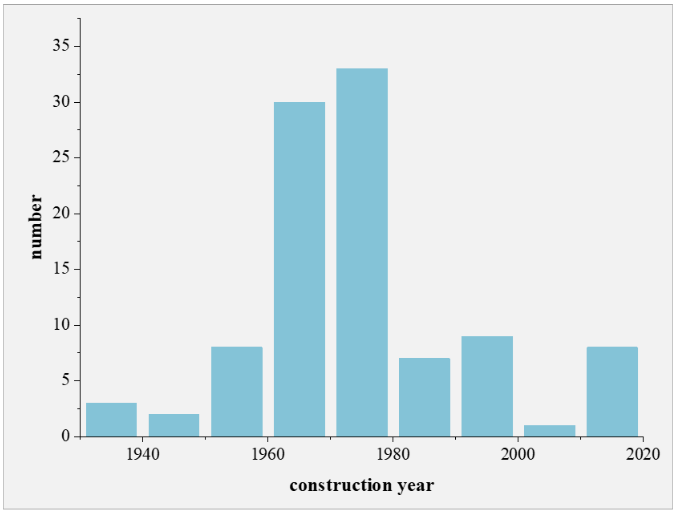

Figure 1: Age of the structures with monitoring

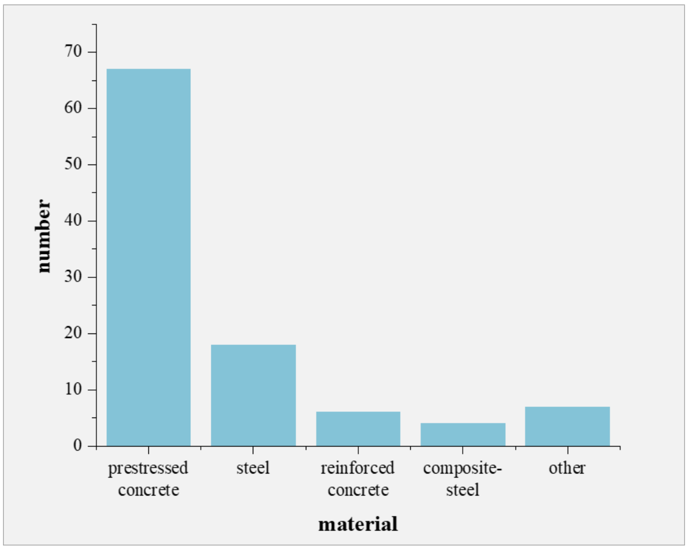

Figure 2: Material of the bridges with monitoring

The potential that monitoring offers to support maintenance decisions through additional information is not being utilized. Decisions are made on a case-by-case basis, relying on the individual knowledge of the structure managers and their supporting teams.

2.3 Cost-benefit of monitoring

Compared to other compensatory measures such as traffic restrictions, the use of monitoring is applied significantly less frequently. However, the benefit-cost ratio of using monitoring as a compensatory measure is very high. Monitoring allows for the continued operation of a structure under traffic. Alternative traffic-related compensatory measures would include speed limits, the closure of individual lanes, or even entire bridges. Reference [4] demonstrates that alternatives to monitoring have significant economic impacts. These impacts include, for example, congestion costs and detour costs, which in turn lead to increased environmental pollution and loss of travel time.

Increased use of monitoring can therefore also have positive effects on the economy, the environment, and social aspects.

2.4 Use cases of monitoring

To enable a structured analysis of the previous case-by-case decisions regarding monitoring measures, the existing application examples were categorized according to the reasons for implementing monitoring. The goal was to enable a standardized assessment. During the evaluation of the previous monitoring applications, it became evident that a systematic approach can be derived in relation to individual use cases. Use cases are known from the BIM methodology and are derived from the project goals [5].

The following commonly used use cases can be derived: "Monitoring of known locally identified damages," "Monitoring for deficits from recalculations and construction," "Monitoring for determining loads and impacts," and "Construction-related monitoring." (Figure 3) [6; 7].

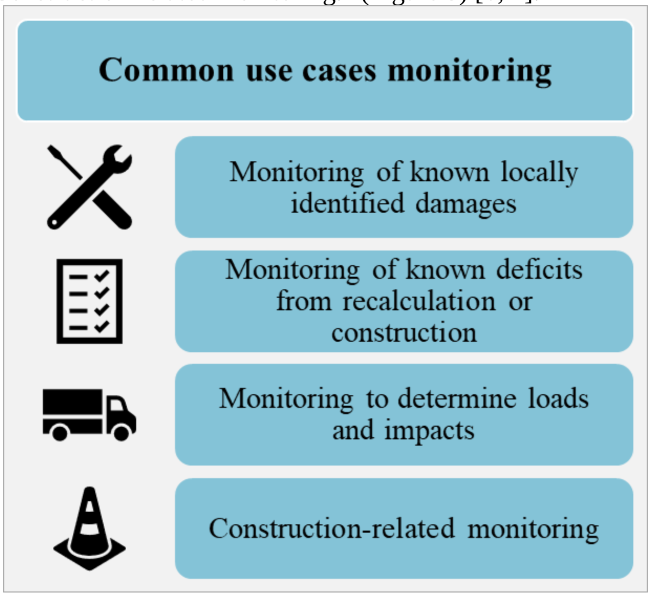

Figure 3: common use cases of monitoring (Modified according to [6])

Monitoring of known locally identified damages is used when structural inspections reveal damages such as corrosion or fatigue cracks. Typically, a local monitoring system is employed to track the progress of damage. The goal is to extend the remaining service life and ensure adequate safety.

Monitoring for known deficits arising from recalculations or due to construction-related factors is used when deficits are identified in a structure or in structures with a similar design. However, visible damage does not necessarily need to be present at this stage. In this case, a global monitoring system can be used to capture the overall structural response, or a local monitoring system can be employed to monitor critical areas. Examples of this use case include structures with stress corrosion cracking or joint connection issues.

Monitoring for determining impacts is used to capture external factors such as traffic loads or climatic conditions. For instance, Bridge-Weigh-in-Motion (B-WIM) systems can be used to determine actual traffic loads. This information is particularly useful in the recalculation of bridges starting from recalculation stage 3 [8].

Monitoring during construction is used to track the performance of structures in real-time while they are being built or if construction work is taking place directly next to the

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structure. This type of monitoring allows for immediate identification of issues such as unexpected deformations or material behavior, enabling timely adjustments. It helps ensure that the structure is being constructed according to design specifications and that any potential risks are mitigated early in the process. Examples include monitoring during the construction of new bridges or during major rehabilitation projects.

In addition to the common use cases, it is also possible to derive use cases with initial use examples, such as the monitoring of special structures or future use cases such as the certificate of birth. However, these applications currently play a subordinate role in the maintenance of structures.

2.5 Challenges in the use of monitoring

The reasons for the limited use of monitoring on federal highway bridges so far are diverse. Figure 4 provides an overview of the challenges that arise throughout the entire process, from planning to evaluation. The main causes include a lack of standardization, insufficient expertise, and missing fundamental principles [9].

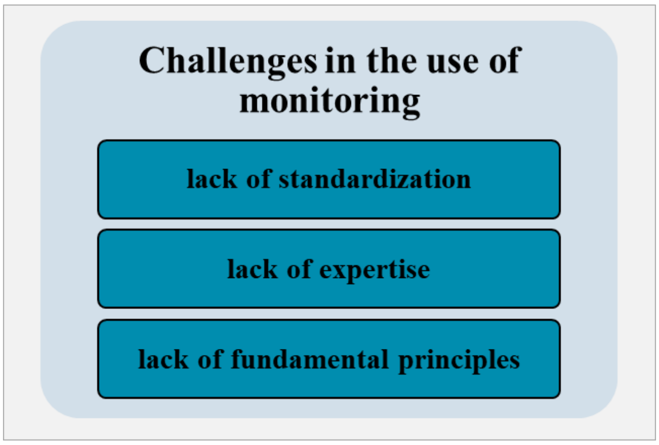

Figure 4: challenges in the use of monitoring

One challenge in the use of monitoring is the lack of standardization. Currently, monitoring is decided on a case-by-case basis, and there are no standardized guidelines for tendering, awarding, evaluating, or selecting a monitoring system. Defining use cases [6], describing individual monitoring methods [10], or outlining processes and stakeholders [1; 2] could help address this issue. In this context, templates for tender documents could, for example, provide valuable support.

Another crucial aspect of the lack of standardization is the absence of an established regulatory process. Currently, the use of monitoring is neither mandated nor recommended in any official guidelines. As a result, a key challenge is demonstrating the economic benefits of monitoring. In cases where damage or deficits are already present, the necessity is usually straightforward to justify, as all alternatives involve compromises in safety or availability. However, if monitoring is to be used proactively as a basis for better maintenance decisions in the future, the cost-effectiveness of the measure must be evaluated. This requirement has led to only sporadic use so far. Approaches from projects such as the “Economic Feasibility Study of Monitoring” offer valuable solutions but are rarely applied in practice [4]. The establishment of standardized processes is still pending. However, with the revision of DIN 1076, monitoring can be integrated into the structural inspection and maintenance process [11; 12]. This step is crucial for a more widespread and targeted use of monitoring. Additionally, incorporating monitoring aspects into existing guidelines, such as the “Manual for the Awarding and Execution of Freelance Services in Road and Bridge Construction” (Handbuch für die Vergabe und Ausführung von freiberuflichen Leistungen im Straßen- und Brückenbau - HVA F-StB), could further support the standardization process [13].

Another important aspect is the lack of expertise. Monitoring involves a high level of complexity, for example, in preparation of a monitoring plan, selecting the appropriate monitoring concept from various offers, or evaluating the results in terms of their significance for structural maintenance. The acquisition of the necessary expertise is not a standard part of the training for those responsible for infrastructure. Therefore, it is essential to either obtain this knowledge independently or compensate for gaps by involving specialized personnel, such as engineering office. The lack of expertise also results in an absence of confidence in applying monitoring effectively, making it difficult to recognize its benefits for structural maintenance.

In some areas, fundamental principles for the use of monitoring are still missing. This is particularly evident in data management. Efficient data collection, reduction, analysis, and storage, as well as the development of user-friendly solutions for all stakeholders, are crucial. At the same time, data security and ownership must be ensured, especially when granting usage rights to third parties. Additionally, integrating monitoring data with structural models and embedding them into maintenance management systems to derive relevant key performance indicators is another essential step toward the broader and more targeted application of monitoring.

3 PROJECTS TO SUPPORT THE TARGETED USE OF MONITORING

3.1 General

At present, various fundamental principles for the targeted and standardized use of monitoring are available. The currently existing foundations include:

- DBV Guideline: "Monitoring: Planning, Tendering, and Operation" (DBV-Merkblatt - Monitoring: Planung, Vergabe und Betrieb“) [1]
- DGZfP Guideline B 09: "Continuous Monitoring of Structures" (DGZfP-Merkblatt B 09 „Dauerüberwachung von Bauwerken“) [14]
- Directive SE05: "Detection of Tendon Wire Breaks Using Acoustic Emission Analysis (Richtlinie SE05: Detektion von Spanndrahtbrücken mit Schallemissionsanalyse) [10]

In addition to these guidelines, several projects have been initiated with the goal of promoting the more widespread and targeted use of monitoring, thereby addressing various challenges. The following research projects have been initiated, conducted, or supported by the Federal Highway and Transport

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Research Institute (Bundesanstalt für Straßen- und Verkehrswesen BASt):

- Documentation: "Monitoring in Bridge Structures" (Erfahrungssammlung “Monitoring bei Brückenbauwerken”) [15]
- Guideline: Strategic Use of Monitoring for Engineering Structures (Leitfaden – Strategischer Einsatz von Monitoring für Ingenieurbauwerke) [2]
- "Birth Certificate" for Bridge Structures (Geburtszertifikat für Brückenbauwerke) [16]
- Documentation on the Application of Innovative Methods in Condition Assessment, with a Focus on Standardized Data Models (Erfahrungssammlung über die Anwendung innovativer Verfahren in der Zustandserfassung insbesondere bzgl. standardisierter Datenmodelle) [17]

The following sections introduce these projects and illustrate how they contribute to developing solutions for existing challenges.

Table 1 consolidates the challenges and current projects of BASt. It assesses the extent to which these projects are suitable for addressing the existing challenges. The results presented in Table 1 are further elaborated in the chapters discussing each individual project.

Table 1: Consolidation of Challenges and Current Projects

challenges	lack of standard-ization	lack of expertise	lack of fundamental principles
documentation of monitoring experience		++	
guidelines to the strategic use of monitoring	+	++	+
birth certificate	+	+	+
standardized data models	+	+	++

3.2 *Documentation: "Monitoring in Bridge Structures"*

In recent years, documentations have been created on several topics commissioned by the BASt. These serve to compile and systematize the experiences gained so far in specific areas [15; 18]. As such, they represent an initial step in preparing a topic for practical application. The documentations have always been structured in an analogous manner, with examples of applications related to bridges being compiled after an initial categorization.

The documentation on monitoring is divided into two main sections: one focuses on the state of the art in monitoring, and the other presents a collection of examples of monitoring measures carried out in Germany [15].

The main section "State of the Art in Monitoring of Structures" defines the monitoring objectives, which primarily focus on capturing various structural responses, such as deformations or crack developments. The measurement techniques applied in practice are assigned to the respective measurement objectives. Additionally, information about the functioning and performance of the measurement technology, as well as the information gained, is provided. Notes on the limitations of monitoring and quality assurance supplement this section.

The second main section contains a collection of examples of selected monitoring measures. The categorization in this part is based on the monitoring objectives developed in the first main section. Building on this, specific monitoring projects and their results are described. The reasons for monitoring, relevant structural features, measurement goals, employed measurement technology, responsibilities in the monitoring process, information gained, and data management are detailed. Additionally, statistical evaluations on tenders, awards, and the responsibilities of the stakeholders in the monitoring process are presented.

The documentation, with its structured and uniform presentation of examples, provides a good entry point into the topic and can contribute to building the necessary expertise in this field.

3.3 *Guideline: Strategic Use of Monitoring for Engineering Structures*

The Guideline - Strategic Use of Monitoring for Engineering Structures was developed based on the requirements of infrastructure managers [2]. The goal of the guideline is to provide a practical guide for the targeted use of monitoring in engineering structures, particularly bridges. The project aims to support infrastructure managers throughout the entire process of planning, implementing, and evaluating monitoring measures.

The research project combined literature reviews, expert interviews, online surveys, and workshops to compile challenges and essential foundations for the strategic use of monitoring. The report defines use cases for monitoring, ranging from monitoring localized damage to the use of digital twins for predictive lifecycle management, and describes the project participants and the process from defining the issue to evaluating the monitoring. Furthermore, the guideline includes practical recommendations for tendering, awarding contracts, contract design, economic analysis, and is supplemented by checklists to support infrastructure managers.

Another key topic is data management; client data requirements were developed to ensure structured storage and analysis of monitoring data.

A key reason for the limited use of monitoring by infrastructure owners is the lack of expertise and standardized procedures. The project can help by providing standards and presenting fundamental principles. Additionally, it plays a significant role in building expertise to address the complexity of the topic. With standardized use cases, a defined process, and potential support services, this project can address these challenges. This also applies to the missing fundamental principles in data management. The development of client data

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requirements has made a first step toward creating foundations in this area.

3.4 *Birth certificate for bridge structures*

The research project aims to develop a comprehensive concept for a "birth certificate" for bridge structures and the foundations for a prototype implementation on a real bridge [2]. The birth certificate serves as the basis for condition monitoring and maintenance planning throughout the entire lifecycle of a structure. Central to this concept is the so-called zero measurement, where the initial condition of the structure – immediately after completion and before being opened to traffic – is captured in detail and systematically using various parameters. This reference state will later serve as a basis for comparison to detect, document, and evaluate changes and damages at an early stage.

The concept defines a wide range of parameters: Physical parameters such as material strains, displacements, as well as natural frequencies and modes provide insights into the load-bearing behavior, while chemical aspects such as chloride content, carbonation depth, and moisture content of the concrete offer essential information about durability. Additionally, the geometric properties of the bridge are recorded – for example, through a georeferenced 3D structural model created photogrammetrically or by scanning methods. This model allows precise localization of all recorded parameters and forms the foundation for future deformation analyses and damage-focused condition assessments.

The birth certificate will be created in a standardized, easily accessible form as a PDF document, containing references to all data sets, models, and measurement data, which will then be stored in the SIB-BW infrastructure database. Furthermore, all information related to the birth certificate will be located within the 3D model, and the data will be linked. This will provide a foundation for supporting predictive lifecycle management through Digital Twins. This represents a crucial step toward more sustainable and efficient use of infrastructure resources.

The project constitutes an important effort to lay the groundwork for the targeted use of monitoring. With the birth certificate, a comprehensive overview of the structural behavior before the opening to traffic is provided. This captures a reference state that will serve as the basis for future deviations. As a result, the acceptance of monitoring can be increased, and a valuable contribution to the standardization and development of expertise in this field can be made.

3.5 *Foundations for data management in structural maintenance*

A workshop with infrastructure managers, the necessary foundations for data management in structural maintenance were developed. It became clear that standardized data models and defined interfaces are essential.

As a first step, a project on "Documentation on the Application of Innovative Methods in Condition Assessment, Particularly Regarding Standardized Data Models" was initiated.

The success and utility of innovative methods, such as the use of monitoring, strongly depend on structured and standardized data management. A relevant foundation of data management consists of data formats and models. The data model here refers to a model of the data to be described and processed in structural maintenance and their relationships with each other. Data models help in structuring, presenting, and understanding data, and serve as a plan for organizing, connecting, and storing the data. For all datasets used and generated in the context of maintenance, including planning and construction, data models and their metadata are required. The goal is to determine structured and standardized data formats, data models, and metadata for the data collected during structural maintenance.

This project aims to establish the missing foundations in the field of data management and standardization.

4 IMPLEMENTATION OF MONITORING IN THE EU

The use of monitoring in Europe is not harmonized, as demonstrated by the Horizon 2020 project “IM-SAFE.” The main goals of IM-SAFE include the development of new European standards for the monitoring, maintenance, and safety of transport infrastructures. This aims to enable well-founded decisions regarding maintenance needs and optimized maintenance strategies [19].

The following technical and organizational challenges were identified during the project [20]:

- Different national regulations and standards complicate the creation of unified European standards. While some countries focus on preventive maintenance, others prioritize reactive measures after damage has occurred.
- Technological advancements require continuous adaptation, but it is complex to incorporate rapid technological changes into standardization processes. As a result, implementations often lag current technological possibilities.
- Heterogeneous responsibilities and interests between public and private infrastructure operators may exist.
- Standardization of data formats and protocols is necessary to enable interoperable use of collected information.
- The implementation of standardized monitoring and maintenance procedures requires significant investments.

Despite these challenges, there are efforts to achieve greater harmonization in standardization. These include initiatives at the European level, as well as the development of new technical solutions that enable more flexible and efficient adaptation to existing standards.

Other European countries already have regulations for the standardized use of monitoring:

In Austria, the RVS 13.03.01 guideline on the monitoring of bridges and other civil engineering structures allows for special inspections (e.g., monitoring) to assess damage. Monitoring does not replace structural inspections but can be used as an additional objective method. Monitoring objectives could include the measurement-based documentation of structural conditions or the early detection of critical structural conditions [21].

In Switzerland, the guidelines for the monitoring and maintenance of civil engineering structures mandate the use of monitoring within the framework of zero and control measurements [22].

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Lombardy, in its newly developed bridge monitoring guidelines, has set the following objectives: increasing safety, efficient maintenance strategies, standardized monitoring, and integrating innovative technologies. To achieve these goals, sensor-based monitoring with various sensor technologies will be used for the continuous collection of key structural parameters. Furthermore, real-time data analysis through the implementation of digital platforms and AI-supported decision-making will be introduced to automate pattern recognition in sensor data for the identification of potential damage. The monitoring will support periodic inspections, and the data will be integrated into existing maintenance strategies. Additionally, the creation of digital twins, including for scenario simulation, is planned. This approach is currently being implemented in nine pilot projects [23].

5 CONCLUSION

The use of monitoring in federal highways is currently limited to a few applications. In all cases, it is a case-by-case decision. To promote and target the use of monitoring to support structural maintenance, ways must be found to address the current challenges (lack of standardization, insufficient expertise, and missing fundamental principles). An overview of the challenges and monitoring use in Europe shows that similar challenges exist here as well. Initial solutions, foundations, and new projects are available, but they still need to be implemented on a larger scale.

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