Capacity for Rail

Towards an affordable, resilient, innovative and high-capacity European Railway System for 2030/2050

Strategies for data collection and analysis

Submission date: 01/08/2017

Deliverable 41.3

This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement n° 605650








Collaborative project SCP3-GA-2013-60560
Increased Capacity 4 Rail networks through enhanced infrastructure and optimised operations
FP7-SST-2013-RTD-1

Lead contractor for this deliverable:

- DB AG

Contributors

- Chalmers
- Trafikverket

Project coordinator

- International Union of Railways, UIC

EXECUTIVE SUMMARY

This report sets out from the state-of-the-art charting of current railway monitoring practices presented in Capacity4Rail Deliverable D4.1.1: "Critical components and systems – current and future monitoring", and in Capacity4Rail Deliverable D4.1.2: "Monitoring-based deterioration prediction".

In the current report, the "ideal" monitoring and maintenance targets as identified in Capacity4Rail (D4.1.2) are contrasted towards existing monitoring and maintenance practices as presented in Capacity4Rail (D4.1.1). The overall aim is to provide the framework for (enhancing) a strategy for efficient data collection and analysis. To this end, the current report complements Capacity4Rail (D4.1.1) and (D4.1.2) by identifying feasibility, suitable placement and operational strategies, and benefits and costs (in a broad sense) of potential monitoring targets.

As mentioned, the report describes strategies for data collection and analyses through enhanced monitoring. One important objective of such a strategy is to provide (mainly) infrastructure managers support in enhancing and optimising the current situation with too many individual monitoring systems that are producing large quantities of data. To this end, the current report provides a foundation for cost–benefit analyses of monitoring actions. In particular, it clearly shows the relation between core operational issues and abilities of monitoring to address these. The considerations and recommendations provided in the current report then need to be supported by a more detailed analysis that accounts for specific circumstances on a national level (e.g. national laws), on a network level (e.g. current status of monitoring), and on a local level (e.g. traffic densities). The approach adopted in the current report is valid also for this detailed analysis.

The report first briefly outlines the background, objectives and scopes of the study. The following sections focus on different areas of monitoring. For each area, the general feasibility of monitoring is first assessed. Then, important aspects in defining monitoring strategies in the field are outlined. In particular, an overall (and rough) cost–benefit analysis is provided for most areas. Finally, recommendations for monitoring in the respective areas are provided. The report is concluded by a final chapter that summarizes the main conclusions and recommendations.

TABLE OF CONTENTS

1 ABBREVIATIONS AND ACRONYMS

Abbreviation / Acronym	Description
KPI	Key Performance Indicators
OCL	Overhead Contact Line system
OOR	Out of Roundness
DB	Deutsche Bahn
D-RAIL	EU Project “Development of the future Rail freight system to reduce the occurrences and Impact of derailment” (01/10/2011 – 30/09/2014)
HRMS	UIC project “Harmonisation – Running behaviour and noise on Measurement Sites” (31/03/2012 – 31/12/2013)
In2Rail	EU Project “Innovative Intelligent Rail” (01/05/2015 – 30/04/2018)
INNOTRACK	EU Project “Innovative Track Systems” (01/09/2006 – 31/08/2009)
IT	Information Technology
RIVAS	EU Project “Railway Induced Vibration Abatement Solutions” (01/01/2011 – 31/12/2013)
IM	Infrastructure manager
TRV	Trafikverket

2 BACKGROUND

This Deliverable D4.1.3 relates to Task 4.1.3 in the Capacity4Rail Description of Work. The task sets out from the charting of monitoring that was carried out in Task 4.1.1 and the identification of suitable monitoring targets related to core operational issues as identified in Task 4.1.2.

It should already at the onset be noted that "monitoring" is used very broadly and any distinction between "monitoring" and "inspection" is often discarded. The reason for this is to avoid overly long discussions on definitions and distinctions when they do not gain the overall purpose of the report.

The current Deliverable D4.1.3 essentially balances the current status of monitoring towards what would be the desired situation. It then makes an overview assessment of benefits with the increased monitoring in contrast to the costs of this increased monitoring. Note that both "benefits" and "costs" are here used in a very broad sense.

Naturally, the operational implementation of these strategies will require an analysis that accounts for specific circumstances on a national level (e.g. national laws), on a network level (e.g. current status of monitoring), and on a local level (e.g. traffic densities). However, the current report provides a foundation for a cost–benefit analysis. In particular, it clearly shows relation between core operational issues and abilities of monitoring to address these. Further, the outlined approach of cost–benefit analysis is applicable also for a more detailed analysis that accounts for local conditions.

3 OBJECTIVES AND SCOPE

3.1 MAIN OBJECTIVES

Key objectives of the analysis in the current report are to identify:

- What are the suitable status indicators as identified in D4.1.2?
- What is the current status of monitoring as identified in D4.1.1?
- What is the trade-off in expanding/revising monitoring strategies?
- How can collection and analysis of monitoring data be simplified?

How detailed a trade-off analysis can be depends on the investigated area. However, in general key aspects are which additional data that is obtained, how this data can be employed, what the benefits (in LCC, RAMS, environmental and other “costs”) of the enhanced knowledge is, and how “costly” the shift will be.

Naturally, the report cannot provide exact figures since these depend on specific circumstances on different levels (as discussed above). Instead the aim is to provide a structured approach to ensure that all decisions regarding altered monitoring strategies have a clear vision on what is to be achieved, which benefits the change will yield and which the related costs are. With such a framework, detailed economical (or similar) assessments can be carried out with relative ease.

The aim of the report is consequently to outline strategies for data collection and analysis that can be used mainly for infrastructure managers, but also for operators, vehicle owners, contractors and others. This strategy relates to the detailed discussion on analysis carried out in D4.1.2. It also relates to data communication as dealt with e.g. in other parts of SP4 of Capacity4Rail. An ultimate aim of such a data collection and analysis strategy would be to facilitate a shift from the current situation where many individual and often isolated monitoring systems exist on many railways. The aim of the strategy would then be to integrate (and gradually replace) these systems into an integrated strategy where the aim of the individual monitoring systems is clear, where the obtained data is analysed so as to make optimum use of them, and where the output from the different systems can be used to obtain a holistic analysis of the entire railway system.

3.2 STRUCTURE OF THE REPORT

To provide a manageable structure, the subsequent chapters are divided based on the subsystems of the railway, which is essentially the same structure as in Capacity4Rail (D4.1.2). Since the structure and the monitoring aims are the same, the overview of the different chapters provided in chapter 5 of Capacity4Rail (D4.1.2) is valid also for this report. For the sake of brevity, this overview is not repeated here.

4 Overall approach and implementation of results

As mentioned above, the current study can for obvious reasons not give precise recommendations (e.g. on the form: monitoring equipment of type X should be employed if the loading exceeds Y tonnes per year). Instead the report evaluates overall feasibility, ranks overall “benefits” and “costs”. From this, general recommendations are given.

It should also be emphasised that any referencing to specific monitoring equipment or products is avoided. One reason is to focus the description on the key features and objectives of the different forms of monitoring without being biased (or allow an accusation of being biased) by certain implementations. Another reason is that by focusing on general principles and not on special products, the time of validity of the report is extended.

Based on the framework, conclusions and recommendations presented in the report the parties to make the decision (e.g. infrastructure managers, operators) need to make a detailed cost–benefit analysis. Ingredients for such an analysis are outlined in the decision tree in Figure 1. Note that the overall approach behind the decision tree should be regarded not as exclusive, but as a generic strategy for decision making in terms of implementing a monitoring system. In fact, the concerned party (IM, operator etc) has to consider its own situation, i.e. the problem to be solved by using monitoring. Thus, it is not a question of just installing a monitoring system, but rather to evaluate what and where to install it, which problems it should solve and to make the most possible use (benefit) of the equipment. The expected benefits and added value of monitoring lie mainly in the optimization of the maintenance planning (predictive maintenance), increase of capacity, reliability, availability, maintainability and safety and the decrease of costs (inspection and maintenance costs and also LCC costs). Note that to obtain these benefits, the obtained monitoring data need to be analysed and interpreted.

Today, too many individual monitoring systems commonly operate side by side aiming to gather a great deal of data in order to get a better knowledge on asset condition, thresholds, key performance indicators etc in order to improve the decision process in maintenance planning. However, monitoring has to be developed as a system approach based on a technical and economic evaluation of monitoring solutions considering the current and upcoming monitoring strategies and the meaningful context of the applied technologies. Monitoring systems should not by default be used only in certain locations and as stand-alone solutions. However, it should be pointed out that the implementation of monitoring systems, particularly on an entire network/fleet, clearly requires the analysis of financial return of investments. Therefore, the focus should be both on the technical performance and on the economic performance of monitoring systems. These objectives need to be handled as a business case.

The initial work in enhancing (or developing) a monitoring strategy is the identification of the area and the asset respectively to be investigated (see blue boxes in Figure 1). The key performance indicators, historic data, current inspection and maintenance practices, and linked costs of the concerned assets are essential information that should be available at the on-set of an analysis. Based on that, the key operational parameters, their impact and cause-effect relationship provide the operationally relevant components of the investigated asset (see red boxes in Figure 1). These steps have essentially been handled in Capacity4Rail (D4.1.1) and Capacity4Rail (D4.1.2) of WP4.1.

In the first orange box in Figure 1 the party to evaluate its monitoring (IM, operator etc) is to indicate whether a monitoring strategy or practice is currently followed. If so, at which location and what kind of data are collected. Especially if there is no current monitoring practice (in general, or in a certain field), the second and third yellow boxes come into play. These are the focus of D4.1.3. They deal with the general feasibility of monitoring, and with the operational & placement strategies and data collection & analysis. Further, they concern efforts needed to manage data storage, handling and documentation of the gathered data.

Reflecting the needs of parties to perform monitoring and the requirements of the Capacit4Rail-project (monitoring systems to be low cost, simple use, maintenance free), the data should be able to be processed into diagnostic information so that failure prevention and a reliable maintenance forecasts can be done. This issue of the diagnosis platform and the assessment of measured monitoring data shouldn't be underestimated and was discussed in detail in Capacity4Rail (D4.1.2). This topic is commonly coupled with legal, procedural and administrative aspects, and also with company IT policies, available or required IT infrastructure etc. However, it is sometimes forgotten that the usefulness of the monitoring data in e.g. maintenance planning is strongly related to the available skills in interpreting the gathered data in a correct way.

Particular emphasis shall be given to the different types of costs to be considered in the investment in monitoring systems. These costs include, but are not limited to:

- Investment, maintenance, operation, migration
- Costs for IT infrastructure, software & data processing
- Costs incurred due to disruptions, extreme weather, hazards, risks e. g. of erroneous measurements or of operational disruptions
- Costs for general process modifications (e.g. due to modifications of decision- and action-trees) within the concerned organizations.

It is important to note that this approach does not consider any detailed specifications of generated values since these depend on the individual application. Consequently, they need to be indicated by the parties (IMs, operators etc) to allow for a detailed cost-benefit analysis as a part of these parties decision-making process.

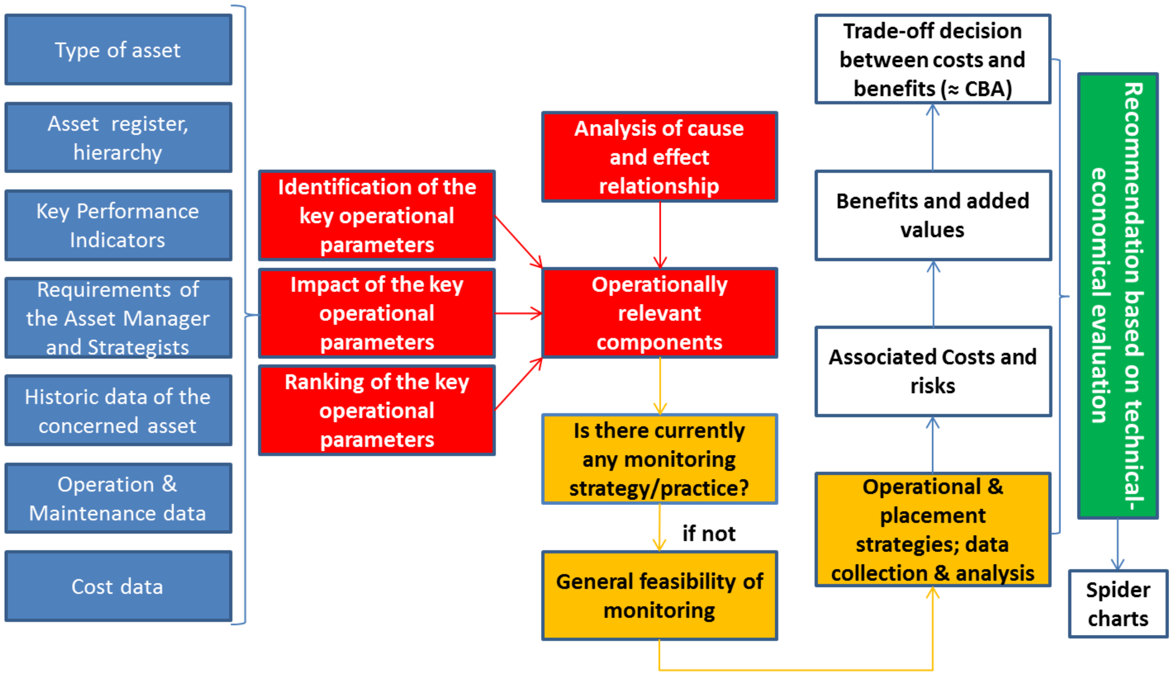


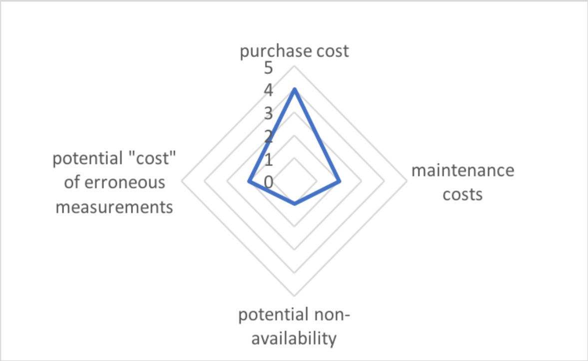
FIGURE 1 DIAGRAM OF DECISION TREE FOR MONITORING RECOMMENDATIONS

In the following sections, “radar charts” (or “spider charts”) are used to provide rough quantifications of “costs” and “benefits” for different monitoring systems in an overall manner (as exact “costs” and “benefits” will differ significantly between use cases, as mentioned above). Examples of such “radar charts” are presented in Figure 2. Here “costs” are divided into the four categories:

- Purchase costs – the cost of buying and installing the equipment
- Maintenance costs – the cost of running the equipment
- Potential non-availability – the cost if the equipment is not functioning; this could e.g. be generated by the need to stop trains
- Potential cost of erroneous measurements – the cost generated by actions due to false alarms

The “benefits” are also divided into four categories:

- Improve safety – the benefits from avoiding accidents
- Improve maintenance planning – the benefits from being able to predict maintenance needs
- Operational control – the benefit from e.g. stopping trains that would cause problems
- Environmental control – the benefit from avoiding deteriorating the environment



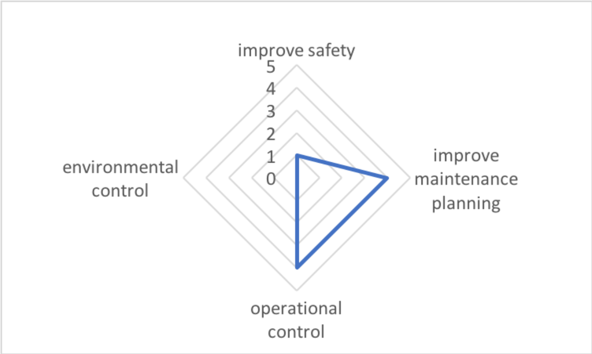


Figure 2 Example of "radar charts" to indicate overall "costs" and "benefits".

The white boxes in Figure 1 indicate work that needs to be obtained by decision making parties (IMs, operators etc). As mentioned, this work concerns evaluation of risks and costs, expected benefits and added values. These analyses can be seen as "high precision radar charts" and are the input for the final trade-off decisions. In this context, it should also be noted that the monitoring strategy must be part of a holistic business case e.g. "infrastructure management" or "fleet management".

It should be noted that the strategic assessment approach outlined in this report can be employed separately for the track and other sub-systems (tunnel, bridge and catenary) as indicated in the report. An additional benefit is obtained if the assessments of these subsystems are (as mentioned above) merged into a holistic analysis related to a business case. However, even more benefit may be obtained if a holistic analysis of the entire system (include all aspects such as operations, maintenance etc) can be performed. Naturally, such an analysis is very complex, but it is also likely to bring significant benefits.

5 MONITORING STATUS OF VEHICLES AND WHEEL/RAIL INTERACTION

This chapter deals with key parameters of vehicle characteristics. The sections of the chapter are selected to reflect different aspects in which the vehicles influence the track. The focus of the chapter is on the vehicle–track interaction. In addition, the vehicles also interact with the power supply system (through the pantograph/catenary interaction, and the wheel–rail grounding). The interaction is dealt with in chapter 10.

5.1 NOMINAL VERTICAL LOAD CHARACTERISTICS

5.1.1 GENERAL FEASIBILITY AND APPROACHES

Nominal vertical load characteristics are preferably controlled using track-based monitoring. In addition, vehicle based measurement systems are possible. However, such systems would primarily be used for the operator to monitor loading etc, and not for continuous monitoring of traffic.

As motivated in Capacity4Rail (D4.1.2), the main monitoring targets are

- Operational frequency of the track
    - number of axles
    - number of trains
- Net loading of the track
    - (quasi-)static wheel load
    - (quasi-)static axle load
    - (quasi-)static bogie load
    - total loads per wagons and trains
    - load per linear metre of the track

To be able to act on the collected data (e.g. in cases of overloading), the system needs also be able to relate the data to the pertinent train, wagon and axle.

As for data handling, transmission should technically be straight-forward. The data could be pre-processed (e.g. to extract the parameters above) to limit bandwidth and storage needs. Special care may be needed to preserve commercial interests (e.g. by not revealing transported volumes from a certain operator) and in cases of international data transfer, cf the work in D-RAIL (http://www.d-rail-project.eu).

Collected data is mainly employed for maintenance and reinvestment related analyses. Here they will give a good overview of the overall loading of the track. This can be employed in overall predictions of track deterioration, energy needs, logistic planning etc.

5.1.2 Placement strategies and/or operational strategies

Essentially there are no changes in transported volumes between connections. Theoretically these may be S&Cs, however in practice major changes are only likely to occur at line intersection. In addition, if cargo volumes from different transport customers are known, overall freight volumes can mainly be calculated. Measurements are then mainly used as validation of predicted volumes and to monitor overloading.

Estimations of overall “costs” related to monitoring nominal vertical loads are compiled in Figure 3

Figure 3 Estimation of “cost” levels for monitoring nominal vertical loads

Estimations of overall "benefits" of monitoring nominal vertical loads are compiled in Figure 4

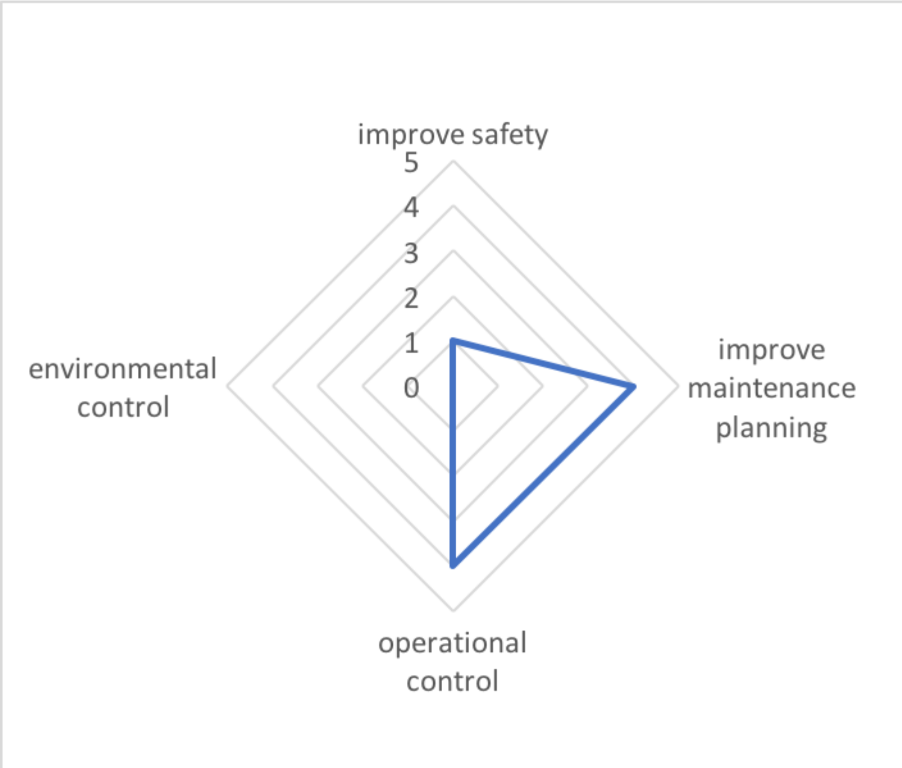


Figure 4 Estimation of "benefits" of monitoring nominal vertical loads

Due to the fairly high installation cost and that cargo volumes often can be estimated in other ways, monitoring of nominal vertical loads is mainly suitable for fairly high-density lines. It may also be more suitable for lines with high axle loads since overloads may be more detrimental on such lines since the allowed axle load tends to be closer to the load carrying capacity of the line. It may be argued that nominal vertical load monitoring is more justified on passenger lines since the load magnitude is less known there. However, the weight of the cargo generally corresponds to a (much) higher proportion of the overall load on freight lines.

5.1.3 Recommendations based on technical and economic considerations

In general, vertical loads are measured to ensure that wagons are not overloaded and to identify malfunctioning running gear. Here, monitoring of nominal vertical load magnitudes is often combined by monitoring of impact load and load imbalances. This synergy can be seen as a reduced purchase cost since monitoring of nominal vertical load magnitudes essentially "comes for free" in such a configuration. Under such circumstances, it makes very sense to monitor nominal vertical load. Note however that to really benefit from this monitoring the collected data needs to be evaluated to identify overloading, and to predict maintenance needs. This require additional knowledge, analyses and algorithms.

Dedicated measurements solely on nominal vertical loads can also be motivated e.g. before trains are entering sensitive track sections, bridges etc. If this is an ideal approach needs to be considered on a case-by-case basis.

The collected data could be used to evaluate the amount of transported goods/passengers, which could be considered to be sensitive information. In particular, there may be issues at cross-border passages.

Care needs to be taken regarding alarm limits. A stopped train may cause significant traffic disruptions. If possible the sensors should be placed close to stations where trains can be inspected without disturbing the traffic. For this reason, a "green–yellow–red" alarm scheme with an intermediate warning level, may be suitable. Further, if alarms are directly linked to detectors, it is vital that false readings are avoided (e.g. using "continuous calibration" towards trains of standard weight, analysing and keeping track of "suspicious readings" and the related conditions etc.). Here also interaction with on-board monitoring could be used to allow a train that has exceeded an alarm limit to continue providing that on-board monitors ensure the operations to be in a safe state.

5.2 Impact loads and load imbalances

5.2.1 General feasibility and approaches

As discussed in Capacity4Rail (D4.1.2), important impact load parameters related to the risk of rail and wheel breaks are (at least)

- Impact load magnitude
- Time evolution of impact load – time for loading, time for off-loading and time of potential lack of contact
- Impact position in relation to (sleeper) support, and in relation to existing rail cracks – this position will vary between every wheel revolution.
- The lateral position (on the wheel tread) of the impact load – this essentially the position of a wheel flat / irregularity.

To assess load imbalance and the related risk of flange climbing, there is a need to evaluate (nominal loads) on all wagons, and also identify which bogies that relate to which wagons, see Capacity4Rail (D4.1.2) for details.

Currently there are many track-based systems to monitor impact load magnitudes installed, see Capacity4Rail (D4.1.1). Typically, these systems extract information on peak impact load (and also commonly e.g. difference between static and dynamic load magnitudes etc). As discussed in Capacity4Rail (D4.1.2), the time evolution of the impact load is of less value from an infra-manger point-of-view since the alarm limits typically have to employ some “bad case scenario” with respect to the time evolution. The reason is that as the wheel defect evolves, the load characteristics will change (for better or for worse).

To be able to use track based detector data, there is a need to link the data to a certain train, wagon, wheelset and wheel. In theory, this can be performed manually. In reality, it would require e.g. RFID tags on the vehicle (and/or bogie). This topic, along with topics of data delivery, regulations etc. are currently discussed in the UIC-project PMD (Prevention and Mitigation of Derailments) with the intention of delivering a draft International Railway Standard.

As for vehicle based monitoring, there are such systems, in particular on high speed trains. Train based systems have the benefit of being able to perform constant evaluation of wheel forces on a train. This can be valuable for health monitoring, maintenance planning etc. Vehicle based systems are usually not suitable for general safety-related monitoring on a line since this would imply that all wagons need to be equipped with a functioning these systems. However, as a complement to track based systems, vehicle based monitoring systems could be used to ensure that a wagon that has registered for too high loads continue its operation in a safe mode (e.g. at reduced speed).

Regardless of detector technology, the collected data can provide useful information if subjected to relevant analyses. Such analyses can be employed to enhance the knowledge of the train fleet status (from track based detectors), or the status of the track (from vehicle based detectors). This includes analyses of how the status evolves.

5.2.2 Placement strategies and/or operational strategies

Track-based sensors should preferably be placed on tangent track to prevent incorrect detections of force imbalances, cf Bäckstedt et al (2012). Further, they should be placed on track sections where the trains have their full operational speed (to result in maximum operational loading), and they should preferably be positioned in connection to stations where vehicles that have exceeded alarm limits can be taken care of.

Vehicle based monitoring on commercial vehicles is usually primarily employed to monitor the vehicle on which the equipment is mounted. However, there are drives to employ commercial vehicles to also inspect the track. This has the benefit of allowing a more frequent monitoring than what is possible by dedicated measurement trains (albeit usually by a lower precision). The prerequisite is that it must be possible to separate the parts of the measured response that are related to the track from those that are related to the vehicle. In other terms, the obtained data must be objective and comparable between measurements by different vehicles. Further, it needs to identify the location of found defects with sufficient accuracy. Procedures for homologation of unattended measurement systems are described in (EN 13848).

Investigations in the European research project D-RAIL have found axle load checkpoints to be cost efficient D-RAIL (D7.4). In addition, they were found to target 50% of derailments (and 75% of derailment costs) together with hot axle box / hot wheel detectors and track geometry measurement systems. Naturally this does not mean that axle load checkpoints can always be economically motivated. A case-by-case analysis of economical and safety implications are needed. Important aspects in such evaluations are an understanding of the likelihood and consequences of wheel load related accidents on the line. This relates to operational parameters such as load (MGT), speed (allowed and actual), axle load, passenger/freight etc.

Similar considerations should be the basis for decisions on how close should measurement stations should be placed (in the case of track based detectors), or how often should measurements be made (in the case of vehicle based detectors. Here it should be remembered that track/rail and vehicle/wheel deterioration is a fairly slow process that typically progresses over months (weeks in extreme cases). However, singular events may cause very rapid changes to the system. Such rapid events typically are wheel flat formation in the case of wheels, and wheel burns or major indentations in the case of rails. Of these, wheel flats generally are more severe. This implies that to detect the “general” deterioration, detectors can be rather sparsely placed (or the track measured with fairly long intervals). In contrast, to place detectors so close that they ensure an early detection of wheel flats is typically not economically feasible. This drawback is somewhat compensated by the fact that wheel flats tend to round off, resulting in a somewhat decreased impact load magnitude.

Estimations of overall “costs” related to monitoring nominal vertical loads is compiled Figure 5.

FIGURE 5 ESTIMATION OF "COST" LEVELS FOR MONITORING IMPACT LOADS AND LOAD IMBALANCES

Estimations of overall “benefits” of monitoring impact loads and load imbalances are compiled in Figure 6. The environmental benefit relates to (indirect) monitoring of wheel roughness.

FIGURE 6 ESTIMATION OF “BENEFITS” OF MONITORING IMPACT LOAD AND LOAD IMBALANCES

5.2.3 RECOMMENDATIONS BASED ON TECHNICAL AND ECONOMIC CONSIDERATIONS

Following the findings in D-Rail (D7.4), the overall recommendation is that axle load detectors commonly are beneficial both from a safety and an economical perspective. To establish the feasibility of a detector in a certain case, a more detailed safety/LCC evaluation is needed.

Commonly impact load detectors are combined with evaluations of nominal loads (cf the discussion in section 5.2), which increases the benefit.

5.3 Vehicle curving, traction and braking performance

5.3.1 General feasibility and approaches

As discussed in Capacity4Rail (D4.1.2), vehicle curving, traction and braking performance relates to mainly to wear and rolling contact fatigue of wheels and rails, but also to track geometry degradation due to track shifting, longitudinal rail shift etc. The latter phenomena will generally decrease deterioration and also increase risks of e.g. lateral track buckling.

Key parameters related to the se phenomena are longitudinal and lateral track forces induced by the vehicle on the rail. Here, mainly magnitude but also time evolution is important. In addition, the damage phenomena relate also to relative slip between wheel and rail, wheel and rail geometry, and the material characteristics. These parameters are considered mainly in section 5.4.

Depending on the sophistication of the traction/braking system, vehicles may be detecting (at least indirectly) longitudinal forces and creep. Curving performance may also be monitored by the vehicle with control of tilting trains and instability detection of high speed trains as extreme examples.

For track-based detectors longitudinal forces are difficult to measure. Also, the longitudinal force relates to the braking/acceleration of the train and is thereby almost completely dependent on the driver behaviour. Consequently, there exist very few (if any) such detectors, cf UIC (2011).

In contrast, there exist detectors for lateral track forces UIC (2011). However, to translate measured lateral forces to vehicle characteristics is difficult. This is partly the characteristics of the running gear is typically not known. Further, the force magnitude will depend strongly on speed and the geometries of wheel and rail. It may therefore be difficult to assess which part of an increased load magnitude that relates to any malfunctioning or deterioration of the running gear. How to deal with this issue depends on the objective of the assessment:

- If the aim is to evaluate the running stability, it is not vital to know exactly which components that add to the instability. A possibility is then to trigger instability (e.g. through gauge narrowing) and evaluate the resulting lateral track forces.
- If the aim is to assess deterioration (or for that matter “track friendliness” of a vehicle), the detection of lateral track forces can be placed in a curve where the speed is constant. The evolution of lateral track forces over time can then be taken as an indication of the deterioration of the running gear. Note that this requires the ability to identify the wagon, and that the influence of e.g. wheel profile deterioration cannot be excluded.

For these reasons, the analysis of the data is more complicated than what is the case for vertical track forces.

5.3.2 Placement strategies and/or operational strategies

Deterioration of running gear characteristics is a slow phenomenon. For this reason, a sparse positioning of sensors is acceptable. Braking malfunctioning may on the other hand be a fast process. However, here sensor strategies typically focus on indirect measures, typically of wheel temperature, see section 5.5.

In general, on-board detection of curving, traction and braking performance is much more feasible (and more employed) than track-based monitoring. This monitoring is mainly targeted at facilitating vehicle operations and maintenance. It may however provide overview information also on track characteristics. Of course, the information is much less precise than what can be obtained by a dedicated measurement train. However, these data relate to much higher costs and operational complications.

Currently, the presence and complexity of vehicle based detectors essentially relates to the sophistication of the vehicle (i.e. the level of control of the traction/braking and curving systems). As for track based systems, these are much rarer than systems measuring vertical loads.

Estimations of overall "costs" of monitoring vehicle curving, traction and braking performance are compiled in Figure 7. Due to the extreme diversity on possible monitoring configurations on trains (where some equipment may be on the limit of being qualified as monitoring equipment), the estimation is made for track based systems monitoring lateral forces.

Figure 7 Estimation of "cost" levels for monitoring vehicle curving, traction and braking performance

Estimations of overall “benefits” of monitoring vehicle curving, traction and braking performance are compiled in Figure 8. The estimation is made for track based systems.

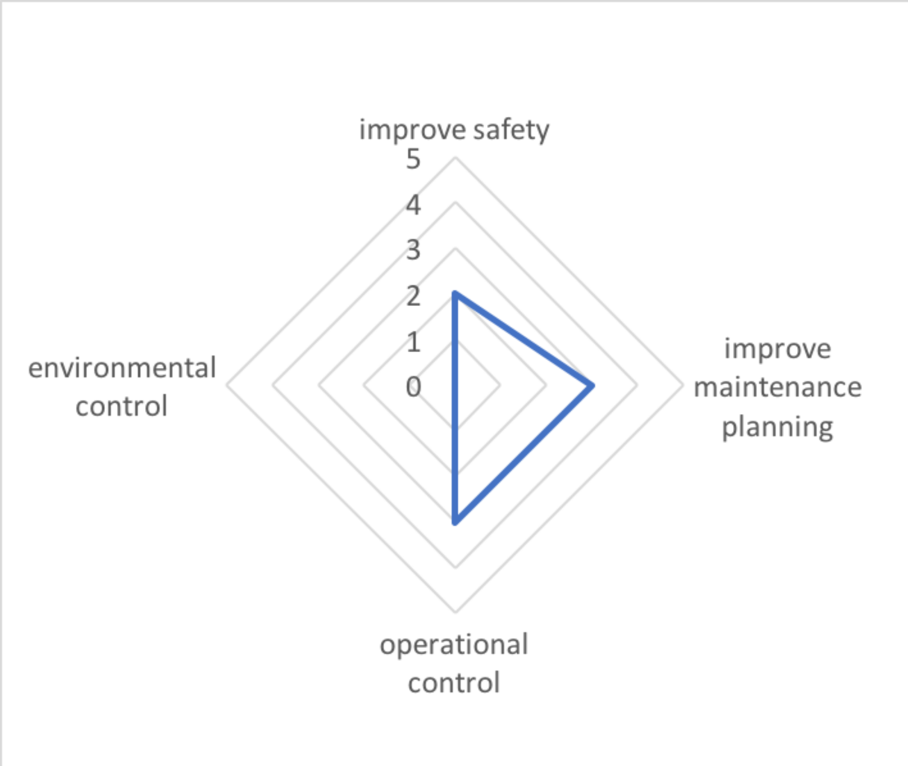


FIGURE 8 ESTIMATION OF “BENEFITS” OF MONITORING VEHICLE CURVING, TRACTION AND BRAKING PERFORMANCE

5.3.3 RECOMMENDATIONS BASED ON TECHNICAL AND ECONOMIC CONSIDERATIONS

For all trains, some monitoring of curving, traction and braking performance is necessary. Here it is the level of monitoring that varies from very rudimentary to highly sophisticated. Historically, this type of monitoring has essentially been employed to control operations. However, the trend is towards more use for purposes such as maintenance prediction. This trend is likely to increase, potentially with an expansion to assessment of track status.

As for track-based monitoring, the general benefits are fairly limited as compared e.g. to measurements of vertical forces. In general, detectors for lateral track forces are mainly an option for specific purposes (e.g. ensuring stability before entering a high-speed line). Track-based detectors for longitudinal forces are even rarer (if existing at all). A possible use case could be brake testing, although there are typically more efficient methods for this.

5.4 Wheel profiles

5.4.1 General feasibility and approaches

In general, only track-based wheel profile detections makes any sense. Here laser based sensors now have an accuracy and performance that make them viable, cf examples of operational systems in Capacity4Rail (D4.1.2). Benefits of track based systems should mainly be compared to the option of measuring wheel profiles in workshop. In general wheel tread degradation is a fairly slow process on the order of tens of thousands of kilometres before any major effects are seen. There are however exceptions: Poor steering of bogies can result in severe flange wear before 10 000 km, aggressive brake shoe materials may promote early tread wear, and a malfunctioning brake system may lead to wheel flats. Note however that the former two cases are significant system issues and that a wheel flat is detected in an impact load detector.

Consequently, the case for track based monitoring is essentially that the wheel is fairly seldom in a workshop, or that workshop measurements are outside the control of the inspecting party (e.g. an infra manager), or that a more detailed evolution is desired.

The wheel profile will affect wheel–rail loads (lateral, longitudinal and to some extent vertical). This will affect the deterioration of wheel and rail e.g. through wear and RCF. To assess the condition of the wheel, the wheel profile measurement should ideally measure not only the lateral profile, but the full 3D geometry of the entire wheel tread. Naturally this poses much higher demands on the measurement system.

5.4.2 Placement strategies and/or operational strategies

As mentioned, wheel profile deterioration is (with some exceptions) a slow process. Track-based sensors can thus be placed sparsely (with the extreme case that measurements are only performed in workshops).

Typically, laser installations are sensitive for pollution (in the broad sense including everything from rain to dirt). This needs to be accounted for in design and maintenance.

Evaluation of profile measurement data is not straight-forward. In general, the common safety measures (flange thickness, slope and thickness) have little or no correlation to how much the wheel profile will increase deterioration of itself or the rail. To solve this issue, a method to characterise and quantify the quality of a wheel tread profile was developed Karttunen (2014).

It should here be mentioned that track based systems also are important for long-term studies of wheel profile deterioration as new brake systems are introduced (e.g. K- and LL-blocks on freight vehicles). Such studies are aided by the use of RFID-tagging of vehicles. It also allows for statistical assessments of profiles, which aids prediction of degradation rates.

Estimations of overall “costs” and “benefits” of monitoring wheel profiles are presented in Figure 9 and Figure 10. The environmental benefit relates to the ability to detect wheel roughness.

FIGURE 9 ESTIMATION OF “COST” LEVELS FOR MONITORING OF WHEEL PROFILES

FIGURE 10 ESTIMATION OF "BENEFITS" OF MONITORING OF WHEEL PROFILES

5.4.3 RECOMMENDATIONS BASED ON TECHNICAL AND ECONOMIC CONSIDERATIONS

Track based detector systems are now a viable solution. The benefit of these solutions should mainly be compared to workshop based inspections. The benefit achievable by wheel profile monitoring relates mainly to the early detection of wear and material fall-out and the related potential for proactive wheel reprofiling.

5.5 OVERHEATED WHEELS AND BREAKDOWN OF BEARING BOXES

5.5.1 GENERAL FEASIBILITY AND APPROACHES

The LCC assessment in the European project D-Rail (D7.4) demonstrate that hot axle box detectors bring financial benefits in terms of 20% LCC reduction. This statement is moderated by noting that "the outcome of cost–benefit analyses considering hot axle box detection are not favourable due to the density-based placement strategy, the already widespread use and the low maintenance benefits." In other words, hot axle box detectors (and hot wheel detectors) are efficient in preventing derailment. To this end, they need to be placed fairly dense. Once that density is achieved there is a small additional value in improving vehicle maintenance using detector data. The recent introduction of acoustic measurement systems aims for that these systems would be able to detect malfunctioning bearing boxes in an earlier stage which improves possibilities for proactive maintenance.

The required density for track based systems will depend on the rate of degradation of the bearing box, and the acceptable risk levels. To estimate the degradation rate of a bearing box is not straight-forward since it is highly related to the construction and the operational circumstances (e.g. the level of lubricant contamination). To provide an example of detector density, consideration of the above factors has in Sweden resulted in a distance between track based hot axle box detectors in the order of 100 km.

Vehicle-based systems will provide continuous monitoring. However, to be efficient, vehicle based monitoring of overheated wheels and breakdown of bearing boxes requires that all wheels are monitored. If not, there is a need for a back-up track-based system to ensure safety.

Regarding overheated wheels, the data obtained from the detectors is the temperature of the wheel. Overheating typically relates to malfunction of tread brakes, which means that heat is generated in the wheel/brake shoe interface. For this reason, the temperature reading will be rather sensitive to where on the wheel the temperature is measured. Further, contact-free measurements of temperatures are inherently complicated since they relate to the (in the case of wheels relatively unknown) emissivity of the material.

It should here be noted that calibration of hot axle box, and hot wheel detectors is also crucial since too low measurements give too many false alarms, whereas too high readings results in very short time until complete failure.

The latter complication is also valid for hot axle box detectors. If instead acoustic bearing detectors are considered, these complications are replaced by the challenge of distinguishing noise from the bearing from ambient noise. Regardless of detector method, a major challenge is to relate a certain level to a specified status of the bearing box / wheel and – more importantly – a predicted rate of change. In particular, there is a need for a reliable prediction on whether there is a risk of a thermal wheel fracture or a catastrophic failure of the bearing box.

These measures are taken purely from a safety perspective. Regarding maintenance, hot wheel detectors can give indications that the braking system needs an overhaul. Further, acoustic bearing detectors are hoped to give input that can provide input to maintenance decisions on bearing boxes before breakdown. However, in both cases, the impact regarding maintenance is limited.

5.5.2 Placement strategies and/or operational strategies

As mentioned above, hot axle box detectors should be placed at a distance so that boxes where deterioration has progressed to a level where temperature is elevated, but still below the alarm limit will not fail completely before the wheel reaches the next detector. Similarly, acoustic detectors should be placed at a maximum distance where deterioration causing noise below the alarm threshold does not result in catastrophic failure before the next detector. For hot wheel detectors, the primary aim is to have the detectors close enough to prevent a temperature rise from below the alarm limit to that resulting in a thermal wheel fracture at the distance between the detectors. Here additional aims may be to prevent temperatures to reach levels where unacceptable tensile residual stresses are induced and/or to reach temperatures (and sparks from the brake system) that may start a fire.

Vehicle based monitoring is essentially continuous. Here the challenge is mainly to relate detector readings to overall status, to identify any false readings and to define ample maintenance and alarm limits.

As for costs, the lower cost for vehicle based solutions should be placed in context of the need to instrument all wheels. False alarms are generally very costly due to the need for stopping trains and performing additional (manual) measurements before commencing operations. This results in demands for high system robustness and/or frequent inspection/maintenance.

Since these detectors are mainly safety related, the need for monitoring of overheated wheels and breakdown of bearing boxes is largest where consequences of derailments are the largest (i.e. the highest for densely populated passenger lines).

Estimations of overall “costs” and “benefits” of monitoring overheated wheels and breakdown of bearing boxes are presented in Figure 11 and Figure 12. The estimation mainly relates to track based systems.

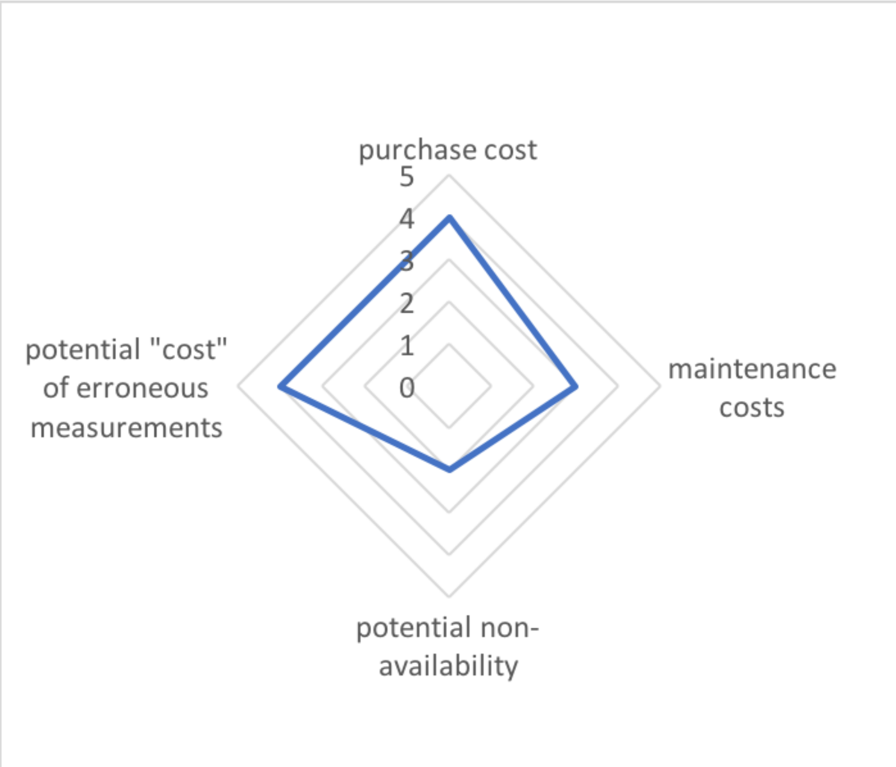


FIGURE 11 ESTIMATION OF “COST” LEVELS FOR MONITORING OVERHEATED WHEELS AND BREAKDOWN OF BEARING BOXES

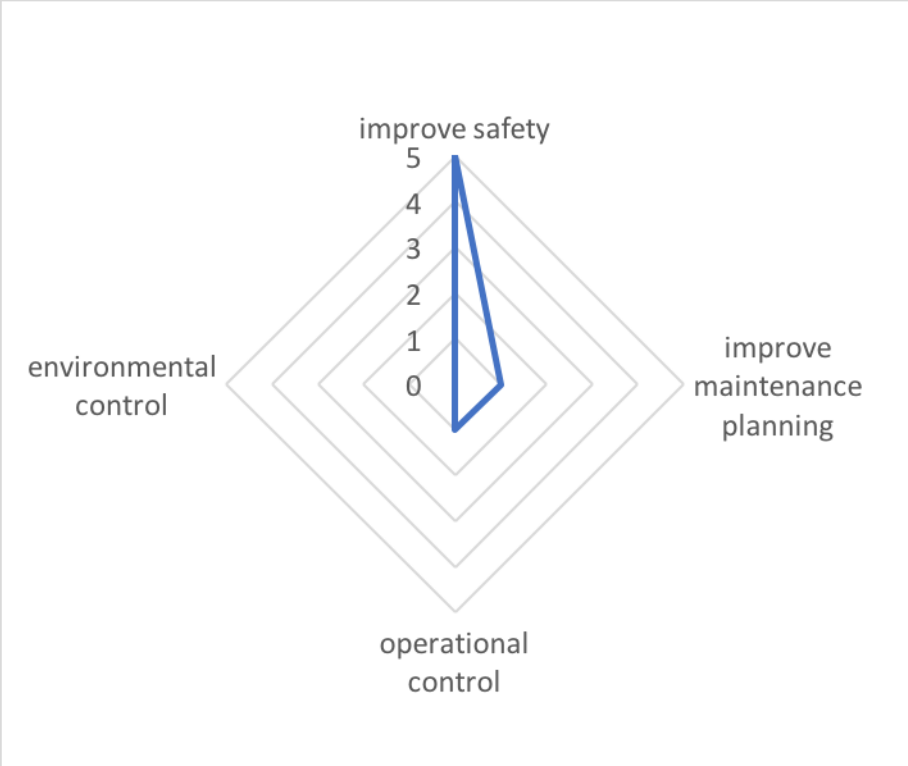


FIGURE 12 ESTIMATION OF "BENEFITS" OF MONITORING OVERHEATED WHEELS AND BREAKDOWN OF BEARING BOXES

5.5.3 RECOMMENDATIONS BASED ON TECHNICAL AND ECONOMIC CONSIDERATIONS

In line with LCC and risk analyses carried out in D-Rail (D7.4), axle box and hot wheel detectors are recommended for derailment prevention. Unless all wheels are equipped with (operational) sensors, track-based detectors will be required if a full coverage is sought for. Wagon mounted sensors may on the other hand be a requirement for some trains.

Axle box and hot wheel detectors are essentially safety devices. They provide little added value to maintenance optimisation.

5.6 NOISE AND VIBRATIONS

5.6.1 GENERAL FEASIBILITY AND APPROACHES

In order to monitor noise and vibration emissions that affect track-side residential areas etc, track-based detectors are used. Vehicle-based noise and vibration monitoring is mainly used to ensure comfort levels for passengers (and typically in validation measurements, and not continuous monitoring).

As outlined in Capacity4Rail (D4.1.2) there are numerous noise emission mechanisms, emission sources and means of transmission. Consequently, a key challenge is to identify relevant emissions that can be related to the studied train. Further, the influence of the surrounding environment and ambient sounds need to be accounted for. Suitable strategies to this end have been investigated by the UIC (2014).

Suitable data from detectors are discussed in Capacity4Rail (D4.1.2). It is clear from the description in Capacity4Rail (D4.1.2) that parts of noise emissions are highly influenced by vehicle characteristics (e.g. rolling noise that is highly influenced by the wheel tread roughness). Other parts are highly influenced by the ambient conditions (e.g. squeal noise that is highly influenced by the humidity). Other parts are "built-in" to the infrastructure (e.g. track and substructure stiffness that influences ground vibrations). This wide spectrum of influencing parameters makes it complicated to define data relevant to e.g. studies of the time evolution of vehicle noise emission.

5.6.2 Placement strategies and/or operational strategies

Placement strategies for track-based sensors are not straight-forward and will depend on what the purpose of data collection is.

If, for example, the aim is to avoid exceeding noise emission levels in certain regions (e.g. cities), detectors should be placed at the entrance to the region. However, they must be close enough so that noise emissions do not change significantly (and any systematic deviations between the conditions at the measurement station and the region need to be accounted for). However, the measurement station needs to be placed far enough so that any unacceptable noise sources may be mitigated.

If on the other hand the aim is to employ measurements as a basis for "noise and vibration related track access charges", the measurement station should be placed in an as undisturbed area as possible, and the measurement site designed towards a maximum degree of objectivity, see (UIC 2014).

The cost and maintenance needs of a measurement station may vary drastically depending on how sophisticated the station should be (here a "bare-bones" set-up could be a single microphone that records the train passing by to allow for wheel flat detection, or a simple accelerometer to assure a building is not affected by detrimental acceleration levels). For the same reason, it is difficult to give general guidelines in when noise and vibration monitoring is suitable.

Noise and vibration measurements are general employed for operational support (with some additional benefits for maintenance planning). Consequently, train operations are seldom affected by measurement results.[1]

Estimations of overall “costs” of monitoring noise and vibration are compiled in Figure 13.

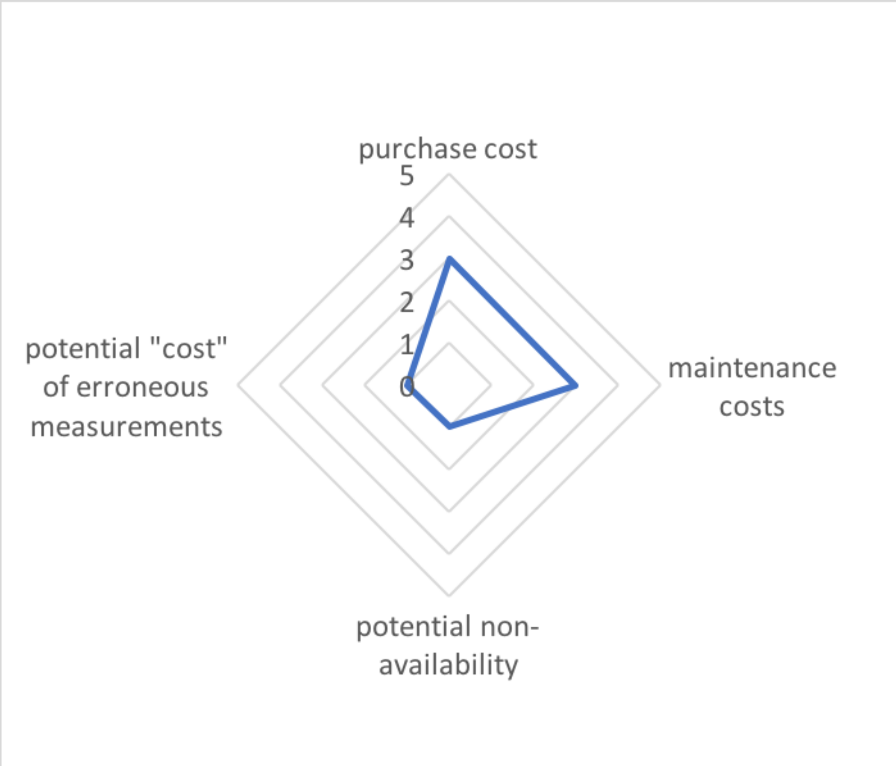


FIGURE 13 ESTIMATION OF “COST” LEVELS FOR MONITORING NOISE AND VIBRATION

[1] The major exception being e.g. acoustic axle box detectors, which are outside the scope of the current chapter.

Estimations of overall “benefits” of monitoring noise and vibration are compiled in Figure 14.

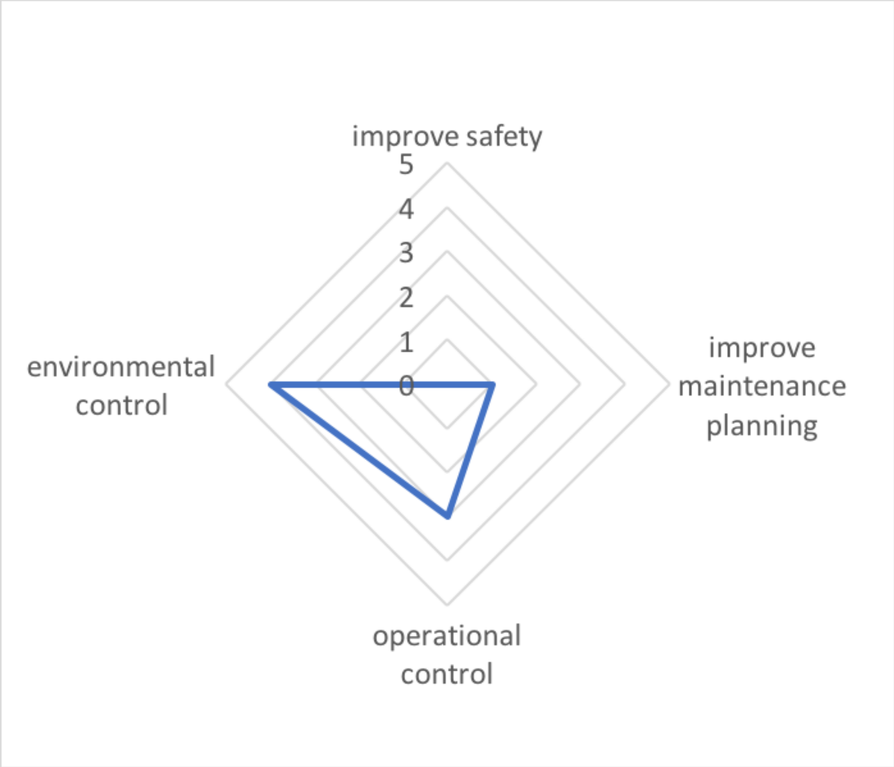


FIGURE 14 ESTIMATION OF “BENEFITS” OF MONITORING NOISE AND VIBRATION

5.6.3 RECOMMENDATIONS BASED ON TECHNICAL AND ECONOMIC CONSIDERATIONS

Monitoring of noise and vibration is mainly related to ensuring environmental standards. Consequently, the needs and benefit for such monitoring is strongly linked to the environmental risks in the form of high noise and vibration levels that exist at a certain location. Objective measurement values (in particular if these are collected over time) are a strong support for discussions with people affected by noise and vibration. They are also useful for assessment of grinding and other mitigating techniques.

5.7 PARTICLE EMISSIONS

5.7.1 GENERAL FEASIBILITY AND APPROACHES

Particle emissions may cause health issues and are therefore regulated, see e.g. (http://ec.europa.eu/environment/air/quality/standards.htm). To ensure that limit values are not exceeded etc, monitoring may be used. In theory, it is possible to monitor particle emissions from both track-based and vehicle-based detectors, see Fridell et al (2010) and Fridell et al (2011). In general, it is however difficult to find a use-case for continuous vehicle based measurements. Continuous track based measurements can on the other hand be useful e.g. in tunnels and at station where they could be part in the ventilation control system.

Data collected from detectors are particle concentrations, in total and by size fractions e.g. PM_{10} (i.e. particles with a diameter between 2.5 and 10 µm, typically measured in µg/m^3) and $PM_{2.5}$ (fine particles with a diameter of 2.5 µm or less).

5.7.2 Placement strategies and/or operational strategies

Particle detectors are preferably placed in locations where there is a risk of (too) high particle concentrations in the air. Typically, this can be tunnels, stations and construction sites. Note that particle concentrations can decrease rather fast with the distance from the emission source and also be affected by air flow (e.g. from ventilation). This makes a relevant choice of placement crucial.

Costs and benefits (in a broad sense) are very difficult to estimate since they are strongly related to local conditions. An attempt at a rough estimation is presented in Figure 15 and Figure 16.

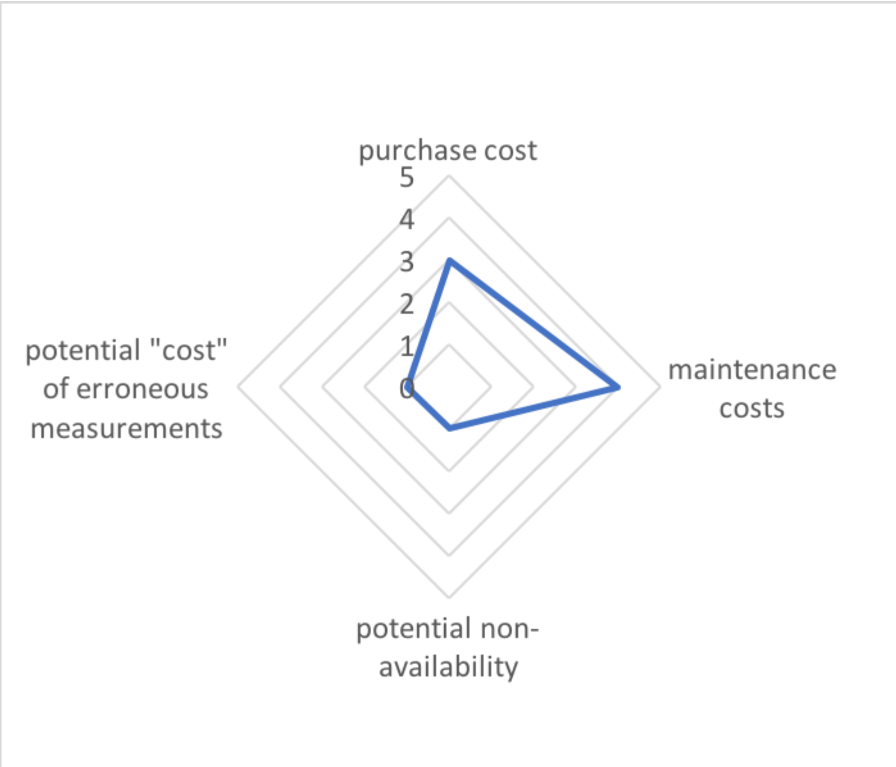


Figure 15 Estimation of "cost" levels for monitoring particle emissions

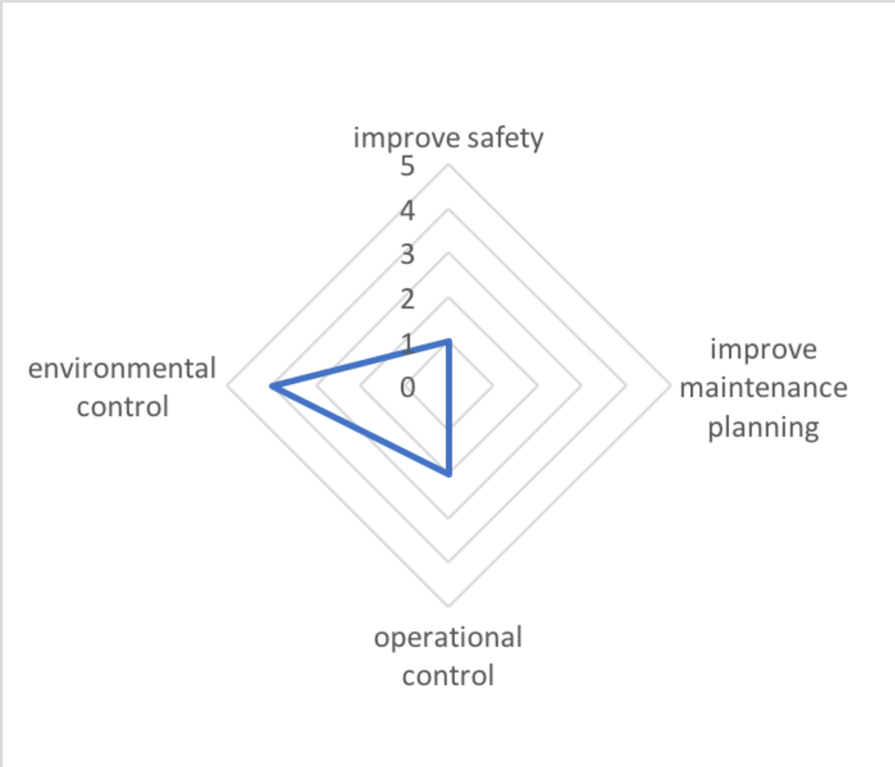


FIGURE 16 ESTIMATION OF "BENEFITS" OF MONITORING PARTICLE EMISSIONS

5.7.3 RECOMMENDATIONS BASED ON TECHNICAL AND ECONOMIC CONSIDERATIONS

Currently particle detectors are seldom used, in particular when it comes to continuous monitoring. The most common current use case is likely in connection to construction sites where there temporarily may be very high levels of particle emissions. In the future, there could however be potential for more detection e.g. at stations in order to optimise ventilation schemes.

6 Monitoring of railway corridor

The current chapter relates to free space for train passage in the railway corridor. It relates to chapter 8 in Capacity4Rail (D4.1.2) where the technical background is described in more detail.

6.1 Clearance gauge

6.1.1 General feasibility and approaches

To assess clearance gauge, vehicle-based monitoring is commonly used. These measurements are mainly intended to ensure that the required clearance gauge is obtained. This is a safety related monitoring activity. In addition, they can map intruding objects and also objects outside the required gauge. The latter can be used as a basis for allowing wider and higher transports based on the actual clearance gauge of the line. Such measurements will support operational planning. To facilitate cross-border traffic, it is vital that clearance gauges are comparable between countries. This topic is investigated by the European Commission (2017) and reports referenced therein.

The study summarized by the European Commission (2017) also considers means of assessing the clearance gauge, including a "best practice" analysis. In the most sophisticated case, the data collected will essentially consist of a 3D mapping of objects in and in the vicinity of the clearance gauge (typically using laser telemetry). It is concluded that such clearance gauge measurement remains costly and capacity-consuming. They are often also complemented by measurements using hand-held trolleys.

To make measurement data useful especially for cross-border operations, there is a need to harmonize data. The study summarized by the European Commission (2017) concludes that such harmonization efforts are underway although there are challenges.

There are of course possibilities to study time evolutions for clearance gauges, but the use for maintenance planning etc is limited, cf. the discussion below on the time-scale of variations.

6.1.2 Placement strategies and/or operational strategies

Variations in clearing gauge is either a fairly slow process (e.g. settlement of constructions close to the railway corridor) or a very fast process (e.g. objects placed in the vicinity of the track). It is not realistic to capture the latter through scheduled monitoring. Monitoring is in many countries always done on new constructed lines before traffic start. Subsequent monitoring can then be carried out with fairly long intervals.

In cases of constructions (even small) close to the track, the measurements should ensure that these do not interfere with required clearance gauge. However, this does not necessarily require a full-fledge vehicle based inspection, but could be carried out by manual measurements.

Vehicle based monitoring of clearance gauge can cause operational disruptions. If these disruptions occur and how sever they will be are will depend on the operational speed of the measurement vehicle. As an example, DB carry out measurements at above 80 km/h, which implies that operations below 80 km/h will not be (significantly) affected.

Costs, maintenance needs etc will also vary significantly depending on the sophistication of the system. Here the most sophisticated systems are naturally employed on lines where faults would be most severe and/or where the need is the largest. This may be high-density lines, but also low-density lines that carry especially wide freight (cf the discussion on special transports in section 7.1.3). In the other extreme, on low density lines with standard traffic, manual inspections are typically sufficient.

Due to the major variation in potential monitoring solutions for clearance gauge assessment, it is very difficult to make estimations of costs and benefits. Attempts at rough estimations are however presented in Figure 17 and Figure 18.

Figure 17 Estimation of "cost" levels for monitoring clearance gauge

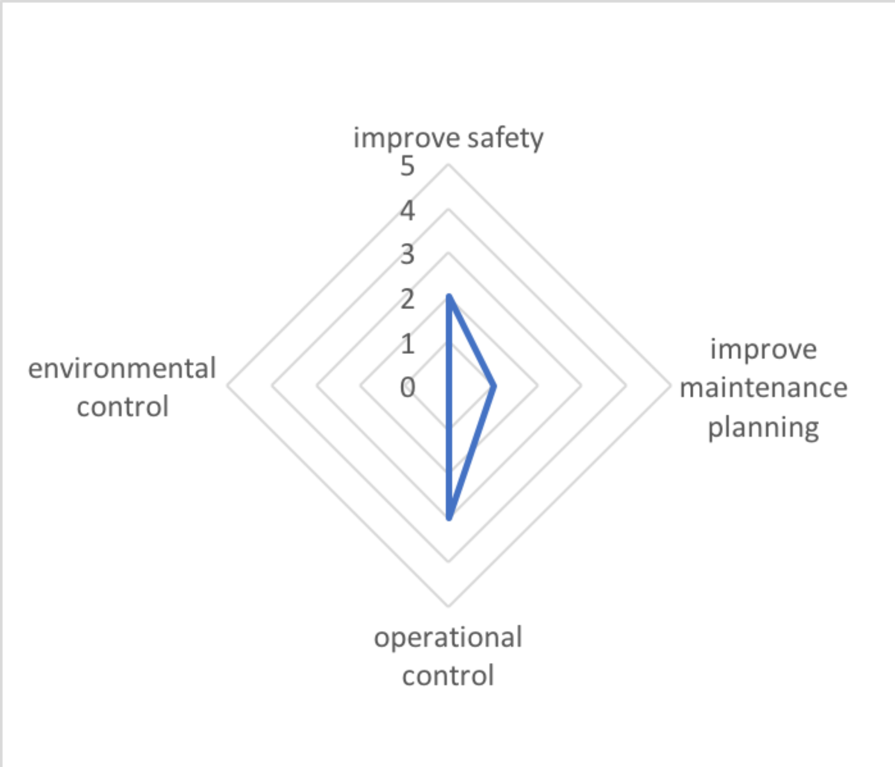


Figure 18 Estimation of "benefits" of monitoring clearance gauge

6.1.3 Recommendations based on technical and economic considerations

The clearance gauge has to be ensured if safe train operations should be possible. This means that clearance gauge has to be monitored in some manner. The question is instead by which accuracy the track gauge has to be measured. Here, costlier vehicle-based measurement typically has an accuracy that allows also for charting of objects that interfere in the track corridor (but not the required clearance gauge). Such measurements may allow for extra wide (or high) transports. Another reason for vehicle based monitoring would be that manual measurements interfere too much on train operations and/or cause issues with worker's safety.

Considerations such as those above should be the foundation for decisions on suitable procedures to inspect (monitor) the clearance gauge. As an example, such considerations have on the DB network (some 65 000 track kilometres) resulted in the decision that the entire network is measured within 4 years, corresponding to approximately 20.000 track kilometres per year. Consequently, the oldest dataset in the DB database is 4 years old. Further, if new constructions are made, measurements with trolleys will be done after the end of the possession.

In for example Sweden special transports are allowed that have a clearance gauge larger than the permitted. Here the inspection intervals are also adapted to such specific demands.

6.2 Trespassing and animals in track

6.2.1 General feasibility and approaches

This type of monitoring relates to avoiding collisions with persons or larger animals.[2] Especially in the case of potential trespassers, an alarm will typically lead to closure of the track. It is therefore vital that the system has a very limited amount of false alarms.

The particular case of suicides and trespassing has been studied in the recent European project RESTRAIL (http://www.restrail.eu/). Within the project, a "practical guideline" was developed. The guideline is intended to support in identifying and analysing the problem, and in selecting, implementing and evaluating the measures taken. The guide also included detailed guidance on specific measures that can be taken. The final output of this project was a toolbox to aid in preventing trespassing and suicides. This toolbox is available on-line (http://www.restrail.eu/toolbox).

The current report has a much narrower focus on monitoring solutions to identify people and (larger) animals in track. For such solutions, typically track-based detection is employed. The reason is mainly that when a vehicle-based detection system triggers an alarm it is already too late for the train to stop. There are however potential future developments with e.g. drone based detectors.

6.2.2 Placement strategies and/or operational strategies

Track-based sensors are typically placed at positions along the track where there are possibilities (and typically have been occasions) of persons entering the track. Detection of animals are rarer (if they exist), but should by the same logic be placed where animals are known to pass the track.

The costs of these types of sensor systems are decreasing (and the capabilities improve). To avoid false alarms (which as discussed above can be very costly) there may be significant needs for maintenance (including manual interpretation of sensor data). This can be reduced by combining monitoring with train operation controls.

Rough estimations of costs and benefits of monitoring of trespassing and animals in track are presented in Figure 19 and Figure 20.

[2] The related topic of vehicle detection at level crossings has been considered out-of-scope for the current project.

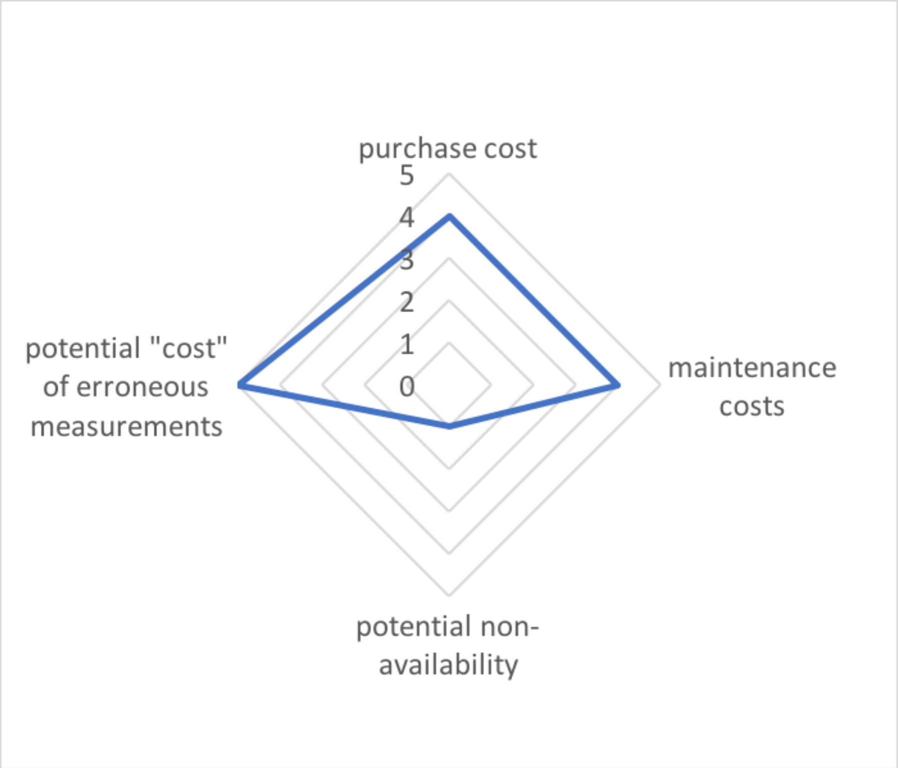


FIGURE 19 ESTIMATION OF “COST” LEVELS FOR MONITORING TRESPASSING AND ANIMALS IN THE TRACK

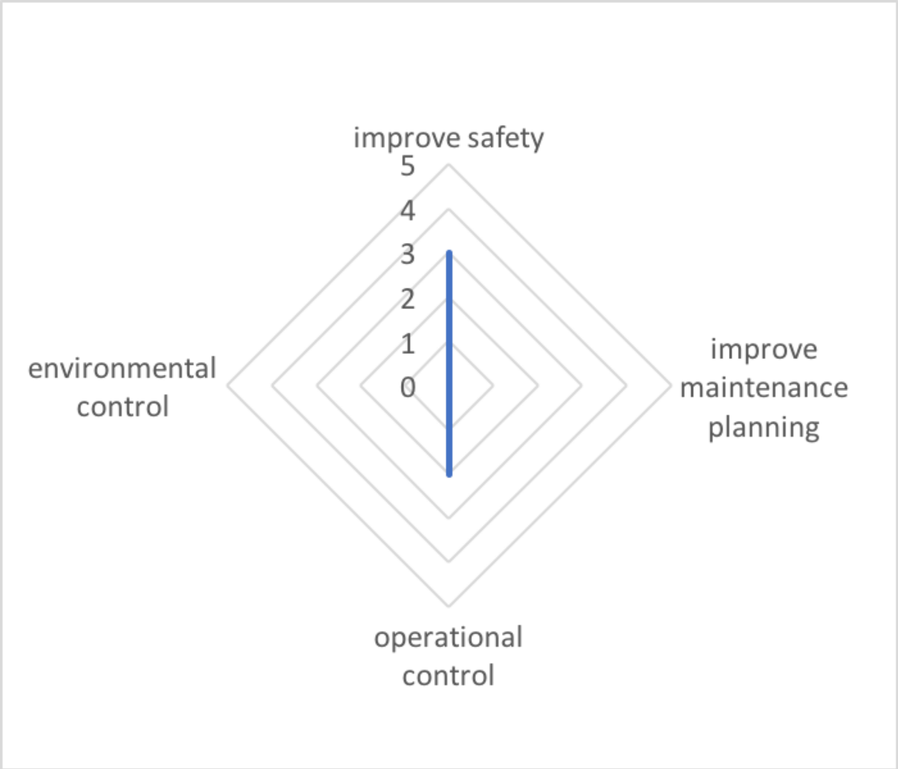


FIGURE 20 ESTIMATION OF “BENEFITS” OF MONITORING TRESPASSING AND ANIMALS IN THE TRACK

6.2.3 Recommendations based on technical and economic considerations

In order to avoid collisions, monitoring of trespassers and animals in track may be efficient. However, practical issues, limits the monitoring to specific track sections (hence the scoring on "safety" in Figure 20.

If the investment is worth the cost relates to a number of considerations, not the least the value in potential saving of lives. Here the opinions vary between countries where this has a high priority, and countries where it is essentially considered to be the individual person's responsibility to stay out of the track. On a more cynical note, similar considerations are also likely to relate to the level of operational disturbances that result from an accident involving trespassers.

7 Monitoring of track

This chapter deals with monitoring of key parts of the track system. This includes also the track construction of switches and crossings. The presentation outlines general feasibility of monitoring and how monitoring of the different parameters can be carried out. It then provides a rough overview of costs and benefits before providing general recommendations.

A more general overview of track maintenance and how monitoring can be included is presented by the UIC (2010).

7.1 Overall condition – track geometry and stiffness

7.1.1 General feasibility and approaches

Track geometry and track stiffness can be monitored using vehicle based systems. By nature, track-based monitoring provides point-measures and is therefore mainly of use in especially sensitive track sections or in the connection to special structures. One extreme example is sections running risks of slope instability. These exceptional cases are however deemed to be outside the scope of the current study.

The obtained data is commonly aggregated to quality indicators. These can be used for maintenance decisions and trending analyses. There are however potential in using raw data with simulations to further understanding the predictive abilities, see e.g. Karttunen et al (2014).

7.1.2 Placement strategies and/or operational strategies

There exists a multitude of vehicle based systems to assess track geometry. These range from fairly rudimentary to vary advanced. In addition to the ability to evaluate the track geometry, an important factor in selecting an appropriate system is the speed at which measurements can be carried out.

As further elaborated in Capacity4Rail (D4.1.2) the track geometry can be divided into nominal geometry and deviations and there are a number of (more or less) standardized status indicators of the track geometry status.

As motivated in D-RAIL (D7.4), track geometry measurement systems can provide a 20% LCC reduction related to freight derailments, provided a measuring accuracy of 90% is ensured. D-RAIL also concludes that track geometry measurement systems have a potential for maintenance cost optimization.

Depending on the track characteristics, the time evolution of track geometry can be considered as a medium to long-term event. In extreme cases (e.g. derailments) the process is instantaneous. Since track geometry typically correlates well to the amount of traffic for modern track with good quality of ballast, more densely operated lines would require more frequent measurements. Further, the demands on track geometry increases with speed, which calls for more accurate and frequent measurements on lines with higher speed.

The amount of available track stiffness measurement systems is much less than the number of systems to measure track geometry. An overview of vertical track stiffness measurements is presented in Berggren (2009). In general, vertical track stiffness deterioration is a more long-term phenomenon than track geometry deterioration – the exception being any seasonal variations. This means that measurements can be carried out more infrequent. Changes in lateral track stiffness may, on the other hand, occur fast e.g. due to ballast displacement. However, for such phenomena lateral track stiffness measurements are likely not the most efficient monitoring approach.

For vertical track stiffness, the absolute magnitude is important, but even more important is the spatial variation. This implies that there is a need for a good resolution of the track stiffness measurements (preferably down to individual sleepers). For lateral stiffness, which relates to track shift and the formation of lateral track buckling there is also a sensitivity to variations along the track. This topic is investigated in In2Rail (D5.3).

Significant decreases in lateral track stiffness and very large decreases in vertical track stiffness (undermined track platform) can be considered as a safety issue (increased risk of lateral track buckling and large track geometry faults). However, the main benefit of track stiffness measurements is in improving maintenance decisions. This mainly relates to modifications (e.g. strengthening) of the substructure to limit settlements and resulting track forces.

Costs and benefits of track geometry measurements and track stiffness measurements are very different. For that reason, these are reported separately in Figure 21 and Figure 22.

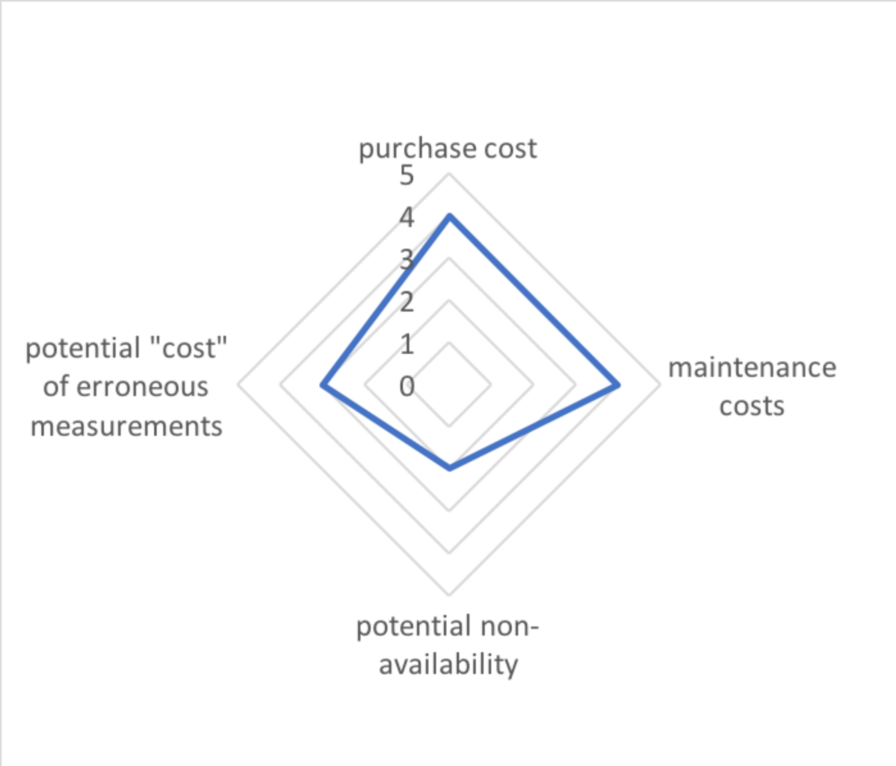


Figure 21 Estimation of "cost" levels for monitoring track geometry (top) and track stiffness (bottom)

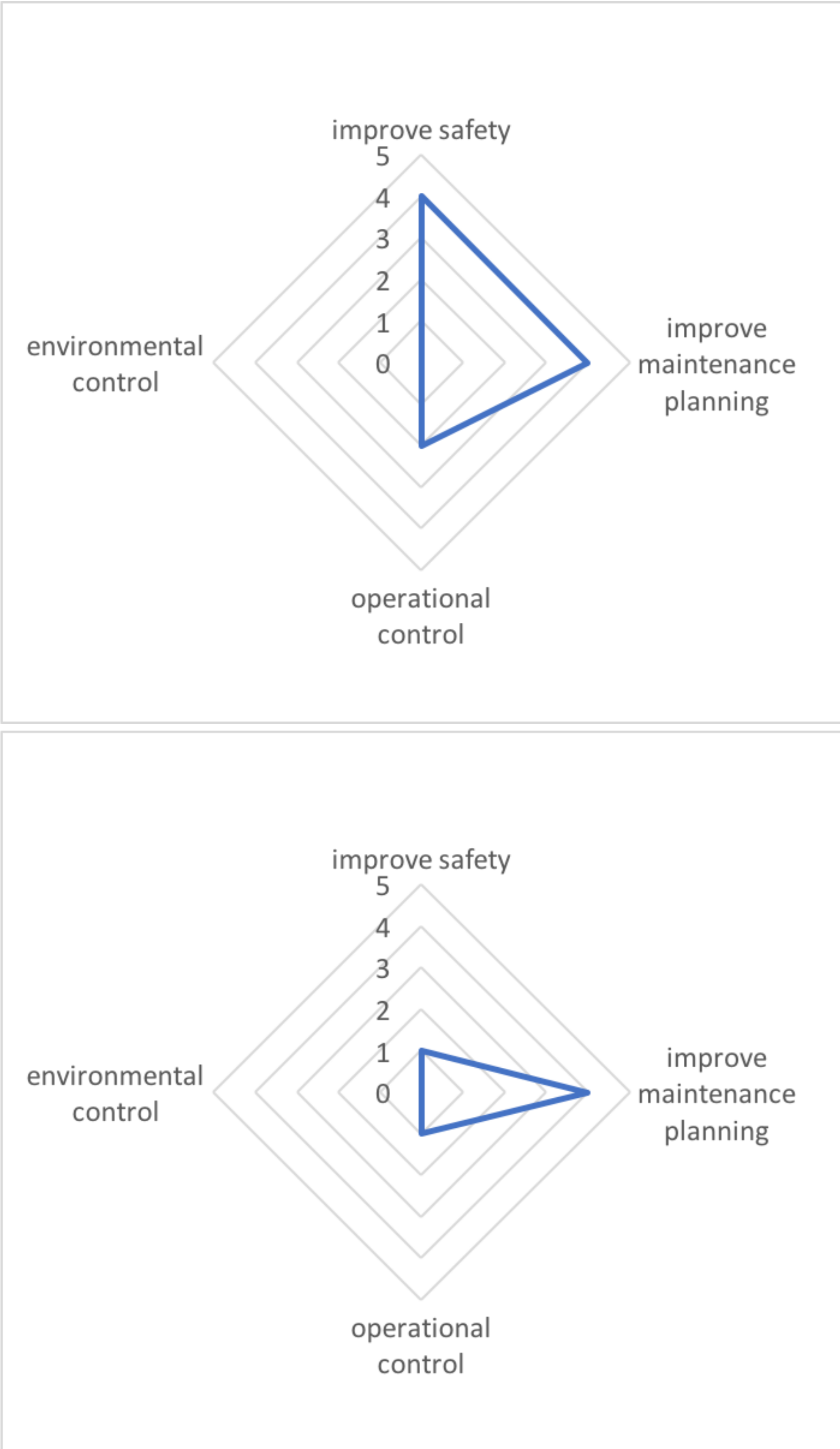


FIGURE 22 ESTIMATION OF “BENEFITS” OF MONITORING TRACK GEOMETRY (TOP) AND TRACK STIFFNESS (BOTTOM)

7.1.3 Recommendations based on technical and economic considerations

Track geometry measurements have been identified as one of the most efficient means of preventing derailments D-RAIL (D7.4) and is now standard procedure for most railways. Then the discussion is more on which precision that should be aimed for and how better prediction of future degradation can be made from collected data.

Track stiffness measurements are rarer. They are however efficient in identifying issues with the track support. This can have a very high potential value since invasive site-measurements and pertinent mitigating actions may be very costly (economically and in terms of traffic disruptions). Vehicle based monitoring can then aid in identifying sections potentially in need of mitigation. These can then be subjected to more detailed on-site investigations.

7.2 Cracks in rails

7.2.1 General feasibility and approaches

Crack monitoring is generally carried out using vehicle-based monitoring. The aim is to establish the location (especially along the track, but also where on the rail profile) and extent of cracking (crack types, crack density and crack sizes).

Precision and capabilities vary depending on equipment and measurement principle. A good precision in characterising occurring cracks may, in addition to safety improvements, aid maintenance and prevention by providing means to identify root causes and to allow for prediction of crack evolution.

There exist a number of methods for detecting rail cracks. Overviews are presented e.g. in Papaelias et al (2008) and Han et al (2014). In general, the “ideal” detection technique should be able to detect size and shape of both small and long cracks at a speed comparable to that of revenue traffic on the line. Currently there exists no such system and the technology employed will be a compromise between the different objectives. In particular, there is a certain need to select between systems that are good at detecting deep cracks (e.g. ultrasonic) and systems that can detect shallow cracks (e.g. eddy current). To overcome these limitations, sometimes more than one technology is employed. Note however that detection of deep cracks is also complicated by the occurrence of shallow cracks that may “shield” the deeper cracks from detection, see e.g. Magel et al (2016).

7.2.2 Placement strategies and/or operational strategies

As cracks grow beneath some 5 mm in depth, they tend to deviate to a (more) vertical growth, see Ekberg and Kabo (2014). This turns the crack growth into more of a safety issue, and also increases reprofiling costs significantly due to the larger grinding/milling depths required. For that reason, it is desirable to find (and mitigate) cracks before they reach a depth of some 5 mm.

Detection of rail cracks is crucial in avoiding rail breaks, which (in particular in cases of multiple fractures) are a safety issue. Rail crack detection therefor has a strong safety objective. In addition, knowledge of existing cracks aids in maintenance planning.

In general rail crack monitoring is carried out on all lines, but with shorter inspection intervals at lines with dense traffic and/or high speeds and/or high axle loads.

Costs and benefits on rail crack monitoring naturally varies with system used. The overview in Figure 23 and Figure 24 aims to give a rough overview for a "typical" system. The environmental benefit relates to the increase in noise emission that a rough rail surface (i.e. a rail with head check cracks and/or material fallout) may give.

Figure 23 Estimation of "cost" levels for monitoring rail cracks

FIGURE 24 ESTIMATION OF "BENEFITS" OF MONITORING RAIL CRACKS

7.2.3 RECOMMENDATIONS BASED ON TECHNICAL AND ECONOMIC CONSIDERATIONS

Monitoring of rail cracks is basically required since operations that are carried out at economically feasible conditions (in terms of speed, axle loads, acceleration/deceleration, traffic density etc) will induce rail cracks sooner or later. Rail crack monitoring is thus a safety requirement, but can – if properly employed – also be useful for maintenance planning purposes.

Inspection frequency needs to be decided based on operational characteristics and allowed risk levels. As for type of system to employ, the discussion above on detection of long versus short cracks should be considered. This relates directly to how useful detection data are for maintenance planning, versus the risk of transverse crack growth and subsequent rail break.

7.3 BROKEN SLEEPERS

The discussion focuses on concrete sleepers. For timber sleepers, the deterioration is typically more visible at the time when the sleeper is replaced and the connection of the fastenings in timber sleepers is typically a critical feature. Further, significant deterioration of timber sleepers can often be found in track geometry measurements since they typically result in significant rail gauge variations.

7.3.1 General feasibility and approaches

Vehicle-based monitoring would be the obvious choice for monitoring of cracked sleepers. As for the methodology, a brief literature survey finds detection methods to be based on dynamic response, e.g. Matsuoka (2015) and vision-based methods, e.g. Delforouzi (2017). To date, the corresponding monitoring systems seem to be in a development stage. As an example, a system aimed at detecting submillimetre cracks at 140 km/h is currently in operational testing on the DB network. When operational, such a system should be able to detect a broken sleeper and inform a maintenance planning system about its location.

7.3.2 Placement strategies and/or operational strategies

Deterioration of sleepers is generally a long-term process. However, sleepers may also crack due to a few overloads (with loading by a derailed wheel being an extreme example. Unless there are a large number of cracked sleepers in an area (or the broken sleeper is massively deteriorated) or due to production issues of a manufacturer, broken sleepers are not immediate safety issues. This implies that inspection can be made at fairly long intervals (as is the case for the currently most common inspection method of manual inspection).

Since the systems are under research/development and there is currently (to the authors' knowledge) no system in day-to-day use, it is very difficult to estimate costs and benefits. Therefore, no such estimations are provided.

7.3.3 Recommendations based on technical and economic considerations

Currently manual inspections are the common procedure to find cracked sleepers. Automated approaches are in development. Once they reach commercialisation, the feasibility needs to be assessed by each infrastructure manager. This relates to costs and benefits, but also the ability of the system to reliably identify cracks.

7.4 Loose fastenings and worn-down rail pads

7.4.1 General feasibility and approaches

As for detection of cracked sleepers, monitoring of loose fastenings and worn-down pads need to be vehicle-based. Also in this case a literature survey reveals vibration based methods, e.g. Wei et al (2017) and computer vision based systems, e.g. Wang et al (2016) to detect loose fastenings. The methodologies are in a research/development stage. When commercialised these systems should be able to identify and establish locations of loose fastenings.

A literature survey reveals no studies on means of directly detecting malfunctioning rail pads. However, based on how the track characteristics change with deteriorated rail pads, potential methods could involve computer vision, vibration based and acoustic based.

7.4.2 Placement strategies and/or operational strategies

Detachment of fastenings and rail pad deterioration are generally long-term processes. Defective rail pads are generally not in themselves a safety issue. Unless there are multiple loose fastenings along a short distance, neither these are a direct safety issue. This implies that inspections can be carried out at fairly long intervals.

Since the systems are under research/development and there is currently (to the authors' knowledge) no system in day-to-day use, it is very difficult to estimate costs and benefits. Automated procedures essentially rely on analysis of track geometry where also other factors can have a significant influence. Consequently, they essentially provide an indication for further inspections. Therefore, no cost/benefit estimations are provided.

7.4.3 Recommendations based on technical and economic considerations

Currently manual inspections are the common procedure to find cracked loose fastenings and defective rail pads. Once automated approaches reach commercialisation, the feasibility, reliability, costs and benefits can be assessed by infrastructure managers.

7.5 Rail profiles

7.5.1 General feasibility and approaches

Apart from hand-made rail profile point measurements, which are deemed outside the scope of the current report, rail profiles can be measured using vehicle mounted systems. The resolution of such systems is on the order of tenths of millimetres. Today rail profile measurements are commonly integrated with track geometry measurements.

Raw data of the rail profile can be obtained. It can then be condensed to key profile measures (e.g. lateral and vertical wear). The measured profiles can be used directly for maintenance planning. To this end, the influence of the rail profile shape on the risk of rail breaks, lateral stability, flange climbing, wear and rolling contact fatigue needs to be addressed, cf e.g. D-Rail (D3.2), Magel et al (2016), Karttunen (2016).

To further support maintenance and operational planning, rail profile evolution over time can be analysed A key issue here is the sampling frequency where (smaller than) decimetre spaced measurements are desirable to be able to compare deterioration patterns.

7.5.2 Placement strategies and/or operational strategies

Rail profile deterioration is typically a fairly slow process. Exceptions may be lateral wear in sharp curves, and crack formation and material fall-out on heavy haul lines. The deterioration rate is influenced by load levels, the matching between wheel and rail profiles, the characteristics of the bogie suspension etc.

The cost of measurement systems depends on the sophistication of the system, but is fairly high. Maintenance needs and robustness are largely related to the use of laser measurements – as these systems get more robust and require less maintenance, so does rail profile measurement systems.

As for most monitoring systems, rail profile measurements provide most value where deterioration rates are the highest and/or consequences of high deterioration are the highest. This includes high-density lines, heavy haul lines and high-speed lines.

Inspection frequency relates to the rate of degradation, which as mentioned above is fairly slow. As rail profile deterioration to a fairly large extent is influenced by the same parameters as track geometry deterioration, combining geometry and profile measurements (see sec 7.5.1) makes sense.

Figure 25 and Figure 26 give estimations of "cost" and "benefit" levels for rail profile monitoring. Naturally costs and precision will vary significantly depending on the system. Consequently, the estimations are very rough.

Figure 25 Estimation of "cost" levels for monitoring rail profiles

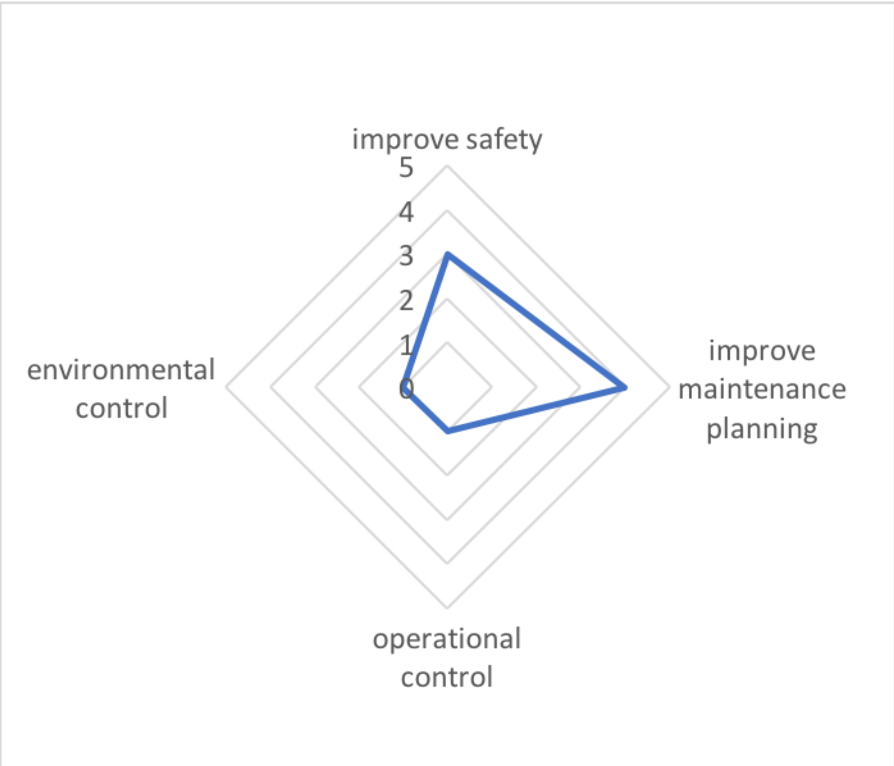


Figure 26 Estimation of "benefits" of monitoring rail profiles

7.5.3 Recommendations based on technical and economic considerations

An infrastructure manager needs to have control of the rail profile. However, as it is typically a fairly slow process, manual measurements may suffice. However, as costs and abilities of vehicle mounted systems decrease, these systems make more sense. This is especially the case if they can be combined with other measurements (e.g. track geometry) and have a sampling frequency sufficient to allow for analysis of rail profile evolution.

7.6 Ballast drainage and frost resistance

7.6.1 General feasibility and approaches

Monitoring regarding drainage and frost resistance need to be vehicle-based if larger stretches of the track need to be monitored. Currently there are to the authors' knowledge no large-scale monitoring of these parameters. Instead identification and mitigation relies on indirect observations e.g. of pools of water, ice build-up etc.

These observations could (at least in theory) be replaced by computer vision based analyses. There should also be possibilities to employ e.g. infrared technology to identify decreased frost resistance through variations in temperature. Such monitoring system could then assist more detailed inspections and/or maintenance actions.

7.6.2 Placement strategies and/or operational strategies

Changes in drainage capabilities and/or frost resistance are generally slow processes. However, lack of functioning drainage capabilities can become dramatic during flooding etc. In general, a monitoring scheme where inspections are rather infrequent (i.e. with intervals in the order of years), but are complemented by additional inspections in cases of extreme weather events (or observations by train drivers or track staff). This is essentially the scheme of manual inspections carried out today.

Whether (automated) monitoring schemes would have any benefits over manual inspections depends on the costs and accuracy of future monitoring systems. Since these are (to the authors' knowledge) not on the market, it is not possible to do a cost–benefit estimation in the current report.

7.6.3 Recommendations based on technical and economic considerations

Once monitoring systems are available, the costs and benefits of these systems can be assessed. A "semi-automated" monitoring system that is potentially already feasible for use is the use of drones to inspect the railway line for sections of potentially poor drainage or decreased frost resistance. The feasibility and benefit of such a system would depend on the current situation. Here not the least safety and security regulations related to the commercial use of drones in the vicinity of the railway is an important factor.

7.7 Condition monitoring for Switches and Crossings – additional parameters

Vehicle based measurements of switches & crossings (S&C) are in essence the same as for rail. However, the measurement of rail profile and corrugation should feature a higher spatial resolution.

- Regarding track geometry, it is possible to have a resolution of 50 mm instead of the 500 mm recommended in (EN 13848-2)
- For corrugation, it is possible to have a resolution of 250 mm instead of 10 000 mm (sampling frequency according to (EN 13848-1) should be at least 625 Hz, but can be 5 000 Hz in today's measurement vehicles)
- For rail profiles, it is possible that have a spatial resolution of 25 mm instead of 1 000 mm (as e.g. used in Sweden).

Beside vehicle based measurement, embedded systems are developed or under development.

Measuring acceleration in transition zones might give a better possibility to plan the maintenance. An S&C has four mayor transition zones (entering and leaving the S&C, the transfer of the wheel from one rail to another at the switch panel and the crossing) and each of these zones induces dynamic loads on the vehicle so there is a probability of higher degradation rates at these zones than for ordinary track.

Measuring the movement of the switch blade is already established.

Measuring rail temperature per heating element is possible, but would need development of a low-cost sensor that can communicate wirelessly. Measurement of current for the heating elements is already established.

7.7.1 General feasibility and approaches

Vehicle-based monitoring is used in the same way as for ordinary track. There are special vehicles to measure S&C that are used in larger station areas instead of manual inspections. These vehicles provide measurements of

- Track geometry (including measures that normally are obtained manually)
- Rail profiles

- Pictures of the rail surface, sleepers and fastenings, as well as the surroundings (which replace the need to walk in track for close visual inspections)

The cost for these system is high but they lower the time in track that otherwise is used for manual inspection. In locations with dense traffic and fairly many S&C this is an established method for infrastructure managers such as ProRail, SNCF and DB. For less dense traffic and for lines with just 4 switches per station, the transportation time between stations limits the capacity and therefore the benefits are lower. Development to measure at speeds up to 70 km/h is discussed. An interesting question here is the necessity to measure both legs or just one leg per S&C. Wither higher speed and if the measurements can be confined to one leg, this method can be used more generally.

Embedded system for measuring acceleration, motor current and temperature are relatively low-cost systems – on the order of 1 000€ or less per parameter. The reliability of some of these systems might need to be considered, but they should have at least 10–20 years in Mean Time Between Failure (MTBF).

For the motor current system, a decrease in the number of failures with 40 % has been mentioned. At a failure rate of 0.5 per S&C and year it would then take some 3–10 years until break-even if the cost of hindrance is some 2 000 € per failure.

7.7.2 Placement strategies and/or operational strategies

Degradation of S&Cs are several parallel processes. The slow processes where it takes several years to see trends are

- Track geometry degradation
- Rail wear degradation

More difficult to predict are failures that will occur in the Point Operating Equipment (POE) where failures might come within weeks or even days. For short failure development time the most interesting failure types are

- Point Operating Equipment, including
    - Point motor
    - Gear box
    - Relays
    - Motor, control and stretcher bars
    - Gliding chair cracking
- Crack development in locations with very detrimental conditions

- Loose components
- Failure of heating elements

Moderate failure development time – up to some two years – include

- General crack development
- Corrugation

The three type of sensors that are covered here are

- Accelerometers
    - Cost, in the order of 1 000 € per unit
    - Needs battery replacement every 5 years
    - MTBF not defined, but should be >20 years
    - Will deliver data every day
- Motor current measurement
    - Cost in the order of 3 000 € per S&C
    - No direct maintenance needs
    - MTBF should be possible to establish from installations already made. Likely to be >20 years per unit
    - Will deliver data every time the S&C is moved or at least once a day
- Temperature measurement
    - Cost, in the order of 2 000 € per S&C (20 sensors in a mesh)
    - MTBF not defined but should be >50 years per unit
    - Will deliver data every hour to the control of the heating system

Motor current and temperature sensors are often profitable as the cost is low and the possibility to lower the number of failures is high. The benefit is largest at high density lines, but also medium dense lines (at least 25 000 tonnes per day) should be possible candidates.

For accelerometers, the benefits for planning maintenance need to be established. The use is more targeted towards cost savings through better planning, and not so much through avoiding failures.

7.7.3 Recommendations based on technical and economic considerations

S&Cs can be monitored by the same technologies used for track. In addition, special monitoring system are recommended for point machines, transition zones and switch heating. The costs for these systems are relatively low. The benefit is still to be evaluated in some cases. It is economical to install monitoring equipment for switches with higher load and dense traffic as the cost for failure is high.

For vehicle based monitoring the development is to measure the same parameters as done by ordinary measurement trains and by visual inspection. The infrastructure manager needs to evaluate the cost against the benefits.

8 MONITORING STATUS OF SUPPORT AND STRUCTURES

Important aspects in the monitoring of bridges and tunnels were discussed in Capacity4Rail (D4.1.2).

The more operational aspects of inspection and monitoring of bridges and tunnels are the focus of the on-going European project In2Track (https://shift2rail.org/projects/in2track/). For this reason, the topic is not addressed in the current report.

9 Monitoring status of the signalling system

Signalling systems are essentially safety-critical systems. For this reason, monitoring and inspections of these systems are broadly covered by laws and regulations. In addition, there can be monitoring and inspection to ensure reliability and prevent malfunctioning. This topic was discussed in Capacity4Rail (D4.1.2).

The more operational aspects of inspection and monitoring of signalling systems are highly dependent on the design and features of the signalling system. Since these aspects differ between suppliers, this topic is excluded from the current report.

10 Monitoring of pantographs and overhead lines

10.1.1 General feasibility and approaches

General monitoring of the electric grid will to a large extent be restricted by the characteristics of the power grid and the control systems available. Since these are parameters that are very specific to each power system, this topic is left out of the discussion below. Instead the focus will be on monitoring of pantographs and contact lines.

Here, a correct position of the contact lines needs to be ensured. Lateral deviations from the correct positioning may result in the pantographs hooking into the line and tearing them down. Vertical deviations, or more commonly rapid variations in vertical positions and/or stiffness, may lead to a loss of contact. In addition, any wear or damage to the wiring should preferably be identified before it causes operational disturbances. Such damage may form from electric discharging, but may also be due to a fatigue and/or creep process.

As for pantographs, their function is to provide a reliable connection to the overhead lines. Lack of continuous contact may lead to electrical discharging that may cause damage to both overhead line and pantograph. Here it is especially the condition of the contact shoe that is vital to monitor. This relates both to defects on the shoe material (typically carbon) and that the pantograph has a sufficient up-lift force.

10.1.2 Placement strategies and/or operational strategies

Monitoring of the overhead lines is preferably carried out by vehicle based monitoring systems, whereas pantograph monitoring is preferably carried out from track based systems to capture all the pantographs of as many vehicles as possible.

Both of these types of systems are readily available on the market. In the case of overhead wire, an optical (including laser) systems. These systems evaluate the wire position with millimetre precision. Such measurements are especially important and complicated at switches and crossings where there may also be electrical sectioning. Another method to measure the position of the contact wire in connection to the pantograph is through inductive sensors, see Capacity4Rail (D4.1.2). Overhead line inspections typically also include an investigation of contact wire wear through optical (including laser-based) methods. Further, they measure the pantograph contact force including potential loss of contact.

As for monitoring the status of pantographs, optical methods are commonly used to evaluate the pantograph uplift force, the status of the contact strip, and the transfer of electrical power, see Capacity4Rail (D4.1.2).

For monitoring of overhead lines and pantographs, there is a need to identify the affected section of the overhead line and the vehicle of the pantograph, respectively. The obtained data can then be analysed based on the criteria outlined in Capacity4Rail (D4.1.2), which relates to the UIC 791 series of Leaflets and the international standard by the UIC (IRS 7109).

Wear and deterioration of overhead lines geometry is in general a slow process unless there are adjustments to the overhead wire. On the other hand, crack formation may be a rapid process promoted by e.g. electrical discharges between pantograph and overhead line. As for pantograph, the damage of the contact shoe may be a fast process. To avoid damage to the overhead line and pantograph from rapidly occurring damage, there will need to be (more or less) continuous on-board monitoring.

Monitoring of pantographs and overhead lines are suitable for all electrified lines. Naturally, the trade-off from monitoring depends on the consequences of related failures (e.g. fracture of contact wires), which in turn depends on the ability of the system to detect and prevent these accidents, the amount of traffic on the line etc. In this context, it can be noted that in general terms, the weakness of the systems discussed above relate to identifying non-visual defects (e.g. related to fatigue and creep) and defects on other parts of the catenary system than the contact wire, although the latter is captured to some degree by some systems.

Rough estimations of costs of monitoring overhead lines and pantographs are presented in Figure 27 and Figure 28. Naturally, actual costs and benefits will vary between systems and applications, so the estimations should be taken as indications for “typical” systems.

FIGURE 27 ESTIMATION OF "COST" LEVELS FOR MONITORING OVERHEAD LINES AND PANTOGRAPHS

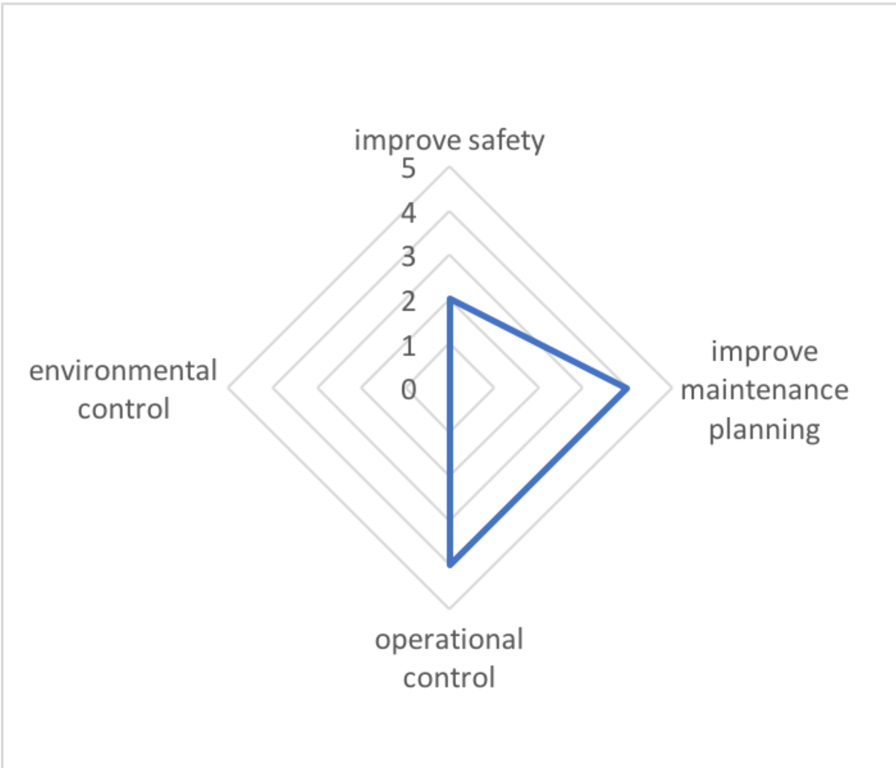


FIGURE 28 ESTIMATION OF "BENEFITS" OF MONITORING OVERHEAD LINES AND PANTOGRAPHS

10.1.3 Recommendations based on technical and economic considerations

Maintaining functioning overhead lines and pantographs is essential since malfunctions may cause significant delays due to fractured overhead lines and/or trains with no functioning power supply. If automated monitoring is the correct procedure to achieve this end will depend on the situation at hand. In general, automated systems are available on the market and widely used. However, the types of systems discussed here (which should be fairly representative for the state-of-art) are not able to prevent all types of failures. There is thus still a likely need for additional manual inspections (albeit at a much lower inspection frequency) even if automated systems are employed.

11 SUMMARY OF RECOMMENDATIONS

This report aims at providing an overview of possibilities and challenges in monitoring and inspection. The focus is on operating vehicles, the track structure and the (mechanical aspects of the) power supply system.

In general, it is difficult and often counter-productive to provide too specific recommendations for monitoring and inspections. The reason is that a suitable strategy for monitoring and maintenance is highly dependent on local conditions. Instead, the report aims to provide an overall approach in enhancing (or creating) a holistic strategy for monitoring and inspection. This approach is visualised in the decision tree in Figure 1. Here, a previous report in Capacity4Rail (D4.1.2) provides support in identifying, evaluating and ranking key operational parameters, identify cause–effect relationship and select methods for interpreting collected data. To improve the strategy further, the current report provides support in deciding feasibility of monitoring, defining placement strategies and evaluating costs and benefits of an (enhanced) monitoring. When it comes to risk analyses related to monitoring and inspections, bases for such analyses can be found in D-RAIL (D7.4). For LCC/RAMS analyses, INNOTRACK D6.5.4 provides a good foundation.

The current report investigates different areas of monitoring and inspections. In general monitoring provides an enhanced knowledge and can be an efficient tool to control and plan operations and maintenance. It should however be emphasized that the collected data need to be interpreted and evaluated in order to identify undesired operational scenarios and to predict maintenance needs. This require knowledge, analyses and algorithms.

To aid in the quantification of costs and benefits, the report provides rough estimations, in each case focusing on four aspects. This analysis shows that the areas of cost and benefit differ significantly between different forms of monitoring. In particular it should be noted that some monitoring may cause fairly severe consequences (mainly in the form of operational disturbances) in cases of erroneous measurements.

A short summary of more detailed conclusions and recommendations for the different areas of monitoring are provided below.

Nominal vertical loads are measured to ensure that wagons are not overloaded and to identify malfunctioning running gear. It is often combined by monitoring of impact load and load imbalances that are a more safety-related form of monitoring. Here care needs to be taken regarding alarm limits since a stopped train may cause significant traffic disruptions. For this reason, a "green–yellow–red" alarm scheme with an intermediate warning level, may be suitable and false readings should be avoided. With these cautions in mind, axle load detectors are commonly beneficial both from a safety and an economical perspective. To establish the feasibility of a detector in a certain case, a more detailed safety/LCC evaluation is needed.

Train-based monitoring of curving, traction and braking performance essentially exists on all trains, but the level of monitoring varies significantly. The amount of such vehicle-based monitoring is likely to expand and in the future also include an assessment of track status for some vehicles. For track-based monitoring, the monitoring of curving, traction and braking performance is more complex (and benefits therefore likely to be more limited) than measurements of vertical forces.

As for wheel profile monitoring, track based detector systems are now a viable solution and the benefit should mainly be compared to workshop based inspections. In this comparison, the frequency of workshop inspections is a key factor.

Axle box and hot wheel detectors are recommended means to prevent derailments, but provide little added value to maintenance optimisation. Track-based detectors are required if all wheels are to be cover by the monitoring actions. Wagon mounted sensors may be a requirement for some trains.

Monitoring of noise and vibration is mainly used to ensure environmental standards. The usefulness is often confined to certain locations. Here it is a useful means to provide objective values and to assess efficiency of grinding and other mitigating techniques.

Monitoring of particle emissions is currently seldom in use outside of construction sites. This form of monitoring may have a future potential for e.g. to optimise ventilation (and cleaning) schemes at stations.

Clearance gauge has to be monitored in some manner to ensure safe operations. More advanced vehicle based monitoring will reduce required time in track, and also provide a charting that can allow for extra wide (or high) transports.

Monitoring of trespassers and larger animals in track may be efficient to avoid accidents. Alarms from such monitoring typically relates to stopped traffic. For this reason, it is crucial that this type of monitoring is very reliable and avoids false alarms.

Track geometry measurement is one of the most efficient means of preventing derailments. It is now standard procedure for most railways and the discussion is more on required precision and better predictive abilities. Track stiffness measurements are rarer, but are efficient in identifying issues with track support. This knowledge can be used for planning of maintenance and reinforcements.

Monitoring of rail cracks in some form is generally required from a safety perspective, but can be useful also for maintenance planning purposes. Important issues to deal with here are required inspection frequency and which crack sizes that should be detected and mitigated.

For sleeper cracks, loose fastenings and worn-down rail pads, manual inspections are currently the common procedure. Automated approaches are likely to be in operation soon.

Degradation of rail profile is typically a fairly slow process, which means that manual measurements may suffice. However, as vehicle mounted systems are getting cheaper and combined with measurements of track geometry, these are likely to be more widely adopted.

Inspection of ballast drainage and frost resistance is currently achieved mainly by manual measurements. Also in this case there is a potential for (more) automated systems.

Switches & Crossings can be monitored by the same technologies used for track, but require special monitoring systems for point machines, transition zones and switch heating. The costs for these systems are relatively low. The benefit is still to be evaluated in some cases.

Monitoring of overhead lines and pantographs is important to lower the risk of overhead line fracture and power failure on trains. Automated systems are available and used. There may however be room for improvement since these systems may currently not be able to prevent all types of failures.

12 REFERENCES

Karl Bäckstedt, Erik Karlsson, Philip Molander & Mikael Persson, Beslutsstöd för underhåll av järnvägsfordon - En studie om utökat användande av hjulskadedetektorer i det proaktiva underhållsarbetet (In Swedish "Decision support for maintenance of rail vehicles – A study on extended use of wheel damage detectors in proactive maintenance activities"), Chalmers Applied Mechanics, BSc Thesis 2013:04, 33 pp (and 6 annexes 1+3+1+1+1+1 pp), 2013. http://publications.lib.chalmers.se/records/fulltext/179646/179646.pdf

Eric Berggren, Railway track stiffness – dynamic measurements and evaluation for efficient maintenance, PhD Thesis, KTH, Stockholm, Sweden, 2009 ISBN 978-91-7415-293-7

Capacity4Rail, Deliverable D4.1.1, Critical components and systems – current and future monitoring, 45 pp, 2016.

Capacity4Rail, Deliverable D4.1.2, Monitoring-based deterioration prediction, 131 pp, 2016.

Ahmad Delforouzi, Amir Hossein Tabatabaei, Muhammad Hassan Khan & Marcin Grzegorzek, A vision-based method for automatic crack detection in railway sleepers, Proceedings of the 10th International Conference on Computer Recognition Systems, pp 130–138, 2017

D-RAIL, D3.2 – Analysis and mitigation of derailment, assessment and commercial impact, 283 pp + annex 18 pp, 2013

D-RAIL, D7.4 – Industry guidelines/standard for the implementation of monitoring techniques, 100 pp, 2014. http://www.d-rail-project.eu/IMG/pdf/DR-D7_4-F2-1-Industry_guidelines-20140930.pdf

Anders Ekberg & Elena Kabo (Eds), Surface fatigue initiated transverse defects and broken rails – an International Review, Research report 2014:05, Chalmers Applied Mechanics, ISSN 1652-8549, 22p, 2014 http://publications.lib.chalmers.se/publication/203928-surface-fatigue-initiated-transverse-defects-and-broken-rails-an-international-review

EN 13848-1:2003+A1:2008, Railway applications – Track – Track geometry quality – Part 1: Characterisation of track geometry, 28 pp, 2004 with amendment 2008

EN 13848-2:2006, Railway applications – Track – Track geometry quality. Part 2: Measuring systems – Track recording vehicles, 35 pp, 2006

European Commission, Measuring and upgrading the clearance gauge of railway lines – Executive summary, Ref no FR01T15B62/DCO/EU/34-16, 21 pp, 2017

Erik Fridell, Martin Ferm & Anders Ekberg, Emissions of particulate matters from railways – emission factors and condition monitoring, Transportation Research Part D: Transport and Environment, vol 15, no 4, pp 240–245, 2010

Erik Fridell, Anders Björk, Martin Ferm & Anders Ekberg, On-board measurements of particulate matter emissions from a passenger train, IMechE Journal of Rail and Rapid Transit, vol 225, no 1, pp 99–106, 2011

Hui Han, Guotang Lu, Peitian Cong, Qi Zhang & Guoyan Wu, development of novel rail non-destructive inspection technologies, Sensors & Transducers, vol 179, pp 121, 2014

INNOTRACK Deliverable D6.5.4, Guideline for LCC and RAMS analysis, 101 pp (and 3 annexes 10+2+2 pp), 2009

In2Rail, D5.3 – Methodology for thermal stress monitoring, *in progress*

Kalle Karttunen, Elena Kabo & Anders Ekberg, The influence of track geometry irregularities on rolling contact fatigue, Wear, vol 314, no 1–2, pp 78–86, 2014

Kalle Karttunen, Elena Kabo & Anders Ekberg, Numerical assessment of the influence of worn wheel tread geometry on rail and wheel deterioration, Wear, vol 317, no 1–2, pp 77–91, 2014

Kalle Karttunen, Elena Kabo, Anders Ekberg, Estimation of gauge corner and flange root degradation from rail, wheel and track geometries, Wear, vol 366–367, pp. 294–302, 2016

Eric Magel, Peter Mutton, Anders Ekberg & Ajay Kapoor, Rolling contact fatigue, wear and broken rail derailments, Wear, vol 366, pp 249–257, 2016

Kodai Matsuoka, Tsutomu Watanabe & Masamichi Sogabe, Damage detection method for sleepers based on vibration properties, MATEC Web of Conferences, vol 24, 7 pp, 2015

Mayorkinos Papaelias, Clive Roberts & Claire L Davis, A review on non-destructive evaluation of rails: state-of-the-art and future development, IMechE Journal of Rail and Rapid Transit, vol 222, pp 367–384, 2008

UIC, Monitoring track condition to improve asset management, ISBN: ISBN 978-2-7461-1871-3, 23 pp, 2010

UIC, IRS 7019: Railway Application - Fixed Installations - Overhead Contact Lines interoperability assessment, ISBN 978-2-7461-2507-0, 35 pp, 2016

UIC, Axle load checkpoints state of the art report, ISBN 978-2-7461-2006-8, 218 pp, 2011.

UIC, HRMS: Harmonization – Running behaviour and noise on measurement sites, 149 pp, 2014.

Ling Wang, Bing Zhang, Jinjin Wu, Hong Xu, Xiai Chen &Wenbo Na, Computer Vision System for Detecting the Loss of Rail Fastening Nuts Based on Kernel Two-Dimensional Principal Component – Two-Dimensional Principal Component Analysis and a Support Vector Machine, Proc IMechE Journal of Rail and Rapid Transit, vol. 230, pp. 1842–1850, 2016

Jiahong Wei, Chong Liu, Tongqun Ren, Haixia Liu & Wenjing Zhou, Online Condition Monitoring of a Rail Fastening System on High-Speed Railways Based on Wavelet Packet Analysis, Sensors, vol. 17, no 2, 12 pp, 2017