Go-Leise
Final report

Deliverable D0

Summary

This final report (deliverable D0) comprises the key findings of the Go-Leise project. The Go-Leise project (Gesamtoptimierung, Lärm-, Erschütterungs-, Infrastruktur- und Sicherheitseinflüsse) aims to optimize the whole track system of the Swiss Railways. The optimization balances noise and vibration levels in the surroundings of the track against life cycle cost and RAMS elements (Reliability, Availability, Maintainability and Safety) of the track system.

In Phase 1 of the project, elements of optimization and references to their impact on noise, vibration and LCC are identified. Phase 1 intends to identify gaps of knowledge and to propose methods to bridge these.

This report highlights the results of all other associated Go-Leise deliverables and combines the results in a holistic optimization approach. It gives an overview of the methodologies for the optimization process and defines next steps to be taken to bridge the most important knowledge gaps. In doing so, it presents an outlook into the next phases of the Go Leise project.

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Motivation and overview of the Go-Leise[1] project

After the introduction of silent freight wagons and mitigation measures like noise barriers, track oriented noise measures represent the next major step: With the retrofitting of the Swiss freight fleet with K-blocks, the scheduled ban of cast iron brake blocks on the Swiss network and the construction of almost 300 km of noise barriers, major efforts in noise reduction have been undertaken. It is therefore reasonable to consider the noise reduction potential of the track as a next step. However it must be kept in mind that the track is a complex system of vibrating elements, interacting with the rolling stock. If one element of the system is changed, this has an influence on all others. Moreover, the optimal combination of track components is different for the various functionalities provided by infrastructure such as noise control, ground borne vibrations control or infrastructure LCC and often they contradict one another. Inevitably and irrespective of the above functionalities all legal requirements concerning safety must be fulfilled.

Aim is to optimize the track as a whole: It is therefore self-evident to assume a holistic view and aim at optimization of the whole system. The idea is to find the optimal combinations of track components – possibly relative to local conditions – which reduce noise and at the same time fulfill the requirements of infrastructure LCC, safety and vibrations in the best possible way. In this process, it is possible that individual components such as the rail pad must be improved. The specific aim in a first phase is to gain an overview of and insight into the topic, define gaps in knowledge and how they can be bridged as well as to define the optimization methodology in detail. This phase should also be used to develop systems of knowledge management and data storage, which can be used throughout the full length of the project. On the other hand the innovation environment should be optimized, including the knowledge management system mentioned; lists of contact persons as well as a compendium of lessons learned shall be developed.

Project in several phases: The project was initially designed to have a total of four phases:

- *Phase 1:* Overview study (overview of topic, define gaps in knowledge, determine experiments and tests to be undertaken, define optimization methodology) The current report is the final deliverable of Phase 1.
- *Phase 2:* Conduct the necessary trials to bridge the gaps in knowledge. This will be undertaken separately for known elements and for innovative changes in the track components. Phase 2 and further have yet to start off
- *Phase 3:* Calculation of LCC, noise and vibration independent of local conditions.
- *Phase 4:* Implement optimization of individual track sections.

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[1] *Gesamtoptimierung, Lärm-, Erschütterungs-, Infrastruktur- und Sicherheitseinflüsse*
(Whole System Optimization for Noise, Vibrations, Safety and Infrastructure LCC)

The scope of the project is straight track. This can be defined as a generic ballasted track system without (narrow) curves that is within specifications and well-maintained: well-aligned track, non-defective fasteners, no hanging sleepers, non-corrugated track etc. In addition we do not consider localized effects related to railway network construction on a larger scale like rail welds, (insulated) rail joints, switches, bridge joints etc.
Phase 1 to be completed by the end of 2016: Work on Phase 1 started in spring of 2015. The results are presented in the present report. This report includes an outlook into Phase 2 and beyond.

2

Introduction and common terminology

For the presentation, understanding and discussion of the knowledge that was collected within the Go-Leise project, it is important to use a common terminology. The following sections summarize the basic terminology and findings from all of the other associated Go-Leise deliverables.

2.1 Railway Noise

Railway noise is considered unwanted sound, generated mainly at the wheel rail interface. Traction noise and aerodynamic noise are considered to be out of the scope of the Go-Leise project as there is no interference with the infrastructure. Railway noise may propagate as airborne noise through the air or as ground-borne noise and vibrations through the ground.

2.1.1 Airborne Noise

Airborne noise is that part of the railway noise that is transmitted through air to a receiver position outside in front of a façade, or through a combination of air and the construction of a building to a position inside the building. Noise is perceived with the ear. **Audible noise** is sound in the frequency band between 16 and 16,000 Hz, whereas **low frequency noise** is defined as sound with a frequency roughly below 100 Hz.

2.1.2 Ground-borne/Structure-borne noise

Ground-borne/structure-borne noises are generated by dynamic movements of solid bodies such as the floor of a house. Structure-borne noise is generated in the vehicle and track system during the passage of a train. (See also 2.1.4)

2.1.3 Vibrations

In the context of the present report, vibrations are ground-borne (they travel through the ground) and perceived (felt) by a person or causing vibrations of buildings or of parts of it. The relevant frequency range of vibrations is between 4 Hz and 80 Hz. In some cases vibrations can lead to secondary effects such as rattling of pottery or doors.

2.1.4 Reradiated sound

The ground-borne/structure-borne noise is transmitted through the soil and the foundation of buildings and is partly reradiated from surfaces (e.g. floor, ceiling) and may thus be audible. Reradiated sound covers the frequency range from 16 Hz to 250 Hz.

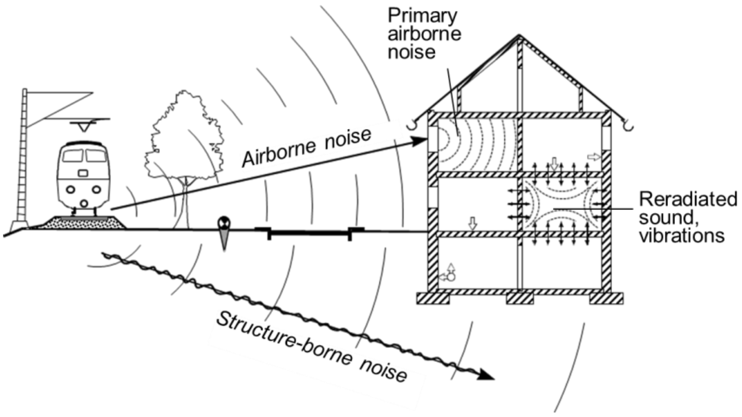

Figure 1 Sketch to illustrate the transmission of structure-borne and airborne noise in the vicinity of an open railway line

The following figure presents the relevant frequency ranges involved in railway noise and vibrations.

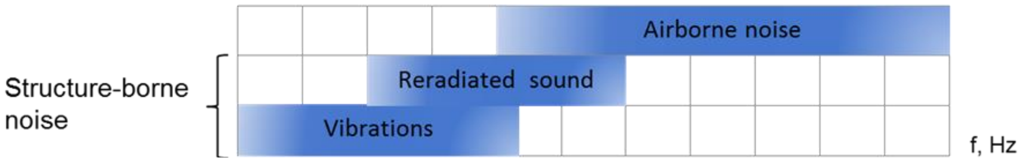

Figure 2 Typical frequency ranges of airborne noise, re-radiated sound and feelable vibrations

A model to describe the generating mechanism of railway noise and vibration is shown in the next figure and explained in more detail in the following paragraphs.

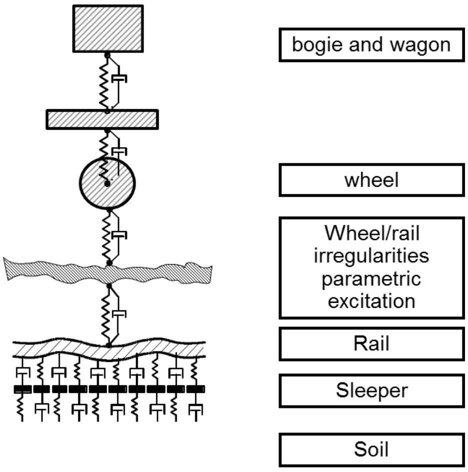

Figure 3 Diagram of wheel/rail impedance models with roughness excitation

Figure 3 shows that both the railway vehicle and the track are involved in the generation process. The Go-Leise focus lies on the track's contribution to the noise emission. It has to be kept in mind that the impact of reduction measures at the track however will depend on both the railway vehicle and the track.
The most relevant terms and effects related to noise and vibration are listed in the following chapter.

2.2 Airborne Noise

2.2.1 Excitation

The vibrations in the rail and track grid are excited at the wheel/rail interface from the (acoustic) roughness (i.e. surface irregularities) occurring on both the wheel tread and the rail head surface. Additional noise is generated from wheel flats or irregularities such as joints on the rail head. Loose rail fasteners and unsupported ("hanging") sleepers can add noise components.

2.2.2 Acoustic roughness

Variations in the height of the running surface of the rail with wavelengths between 5 to 500 mm and amplitudes of a few or several tens of a micrometre are associated with rolling noise excitation. Acoustic roughness can be superimposed by corrugation (periodic wear pattern on the rail head). Acoustic roughness can also be found on the wheel tread. Wavelengths on the wheel are typically between 5 and 50 mm.

2.2.3 Dynamic stiffness (damping)

Dynamic stiffness *k'* is the frequency dependent resistance of an element to deformations due to varying forces. The vibrations observed are therefore the result of the excitation forces acted against (divided by) the dynamic stiffness. Dynamic stiffness is complex, where the real part stands for the stiffness and the imaginary part represents a loss term (i.e. damping). The loss term reflects that in every cycle a portion of the vibration energy is lost (i.e. by conversion of vibration energy into heat).

2.2.4 Rail vibrations

In a broadly excited track system there are certain characteristic frequencies to be found that are of importance to the noise radiation from the rail (see figure 4). They relate to modes in the structure of the track system. Their importance to the noise emission is that they all mark the start of either a stop band (i.e. a frequency band where no transfer of energy takes place) or pass band (i.e. a frequency band where transfer can take place included in a wider range without transfer) thereby drastically changing the size of the vibrating surface. A real track is a complex system where the interdependencies of the corresponding frequencies are not easily acquired. Therefore a simple model is often used to capture some of the interdependencies. Rail and sleeper are approximated as masses interconnected by springs with the dynamic stiffness of the rail pad and ballast respectively.

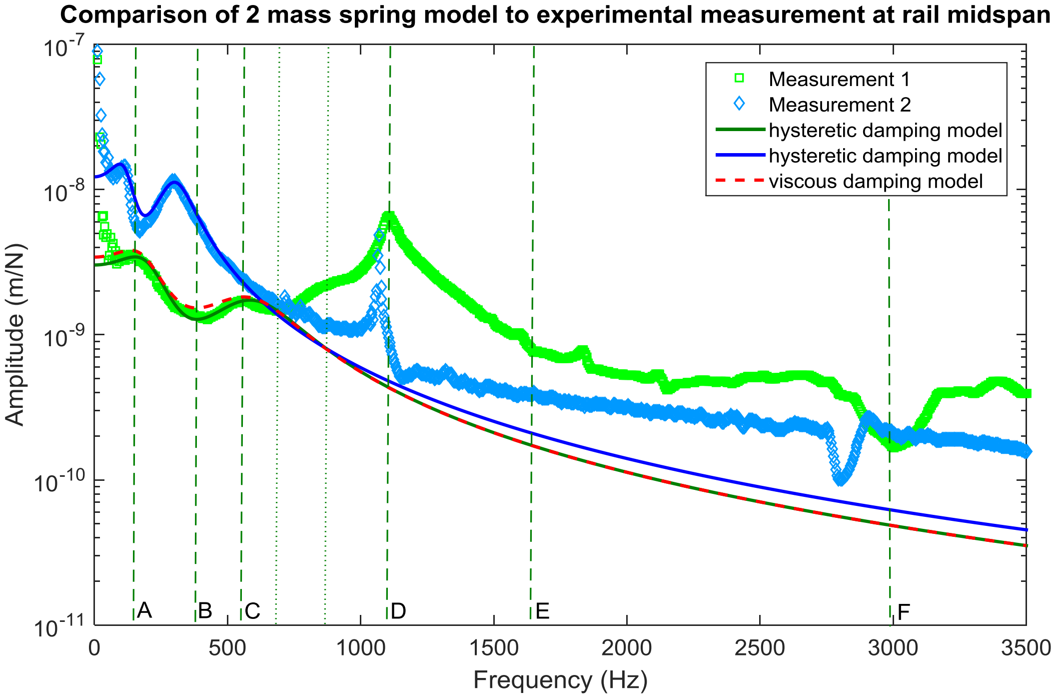

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Figure 4. Illustration of the dominating resonance frequencies for the stiffness in the track vehicle system; analytical models compared to measured values

- ***First cut-on frequency*** is the resonance of the rail grid (rail and sleepers) on the ballast bed

$$f_A \approx \frac{1}{2\pi}\sqrt{\frac{k'_b}{m_s + m_r}}$$

where k stands for the dynamic stiffness, m for the mass per meter and the index b, s and r for ballast, sleeper and rail respectively. The first cut-on frequency marks the start of a pass band for waves to freely propagate along the track grid. Typically, for a ballasted track with UIC 60 rail and concrete sleepers, the first cut on frequency is around 200 – 300 Hz

- ***Second cut-on frequency*** is the resonance of the rail on the rail pad

$$f_C \approx \frac{1}{2\pi}\sqrt{\frac{k'_p}{m_r}}$$

where k' stands for the dynamic stiffness, m for the mass per meter and the index p and r for rail pad and rail respectively. The second cut-on frequency marks the start of a pass band for waves to freely propagate along the rail and therefore the rail is said to be decoupled from the rest of the track system. Typically, this frequency is around 500 to 600 Hz.

- ***Sleeper resonance*** refers to the resonance of the sleeper mass between rail pad and ballast
$$f_B \approx \frac{1}{2\pi}\sqrt{\frac{k'_p + k'_b}{m_s}}$$
where k' stands for the dynamic stiffness, m for the mass per meter and the index p, s and b for rail pad, sleeper and ballast respectively. The sleeper resonance lies in between the first and second cut-on frequency and marks the start of a stop band. The sleeper resonance frequency lies between 400 and 500 Hz.

A fourth characteristic frequency is assembled from an infinitely long rail with discrete supports (sleepers).

- ***Pinned-pinned mode*** is defined by the frequency of a vibration of the rail where half a wavelength matches the sleeper spacing and which has nodes above the sleeper
$$f_D \approx \frac{\pi}{2l^2}\sqrt{\frac{EI_r}{m_r}}$$
where *EI* stands for the bending stiffness, m for the mass per meter, l for the sleeper spacing and the *r* for rail. The pinned-pinned mode marks the start of a stop band for waves travelling through the rail; however there is a second mode at the same wavelength that has its nodes in the bay and a maximum of amplitude at the sleeper position. This second mode is coupled to the sleeper by the dynamic rail pad stiffness and again marks the start of a pass band. The width of the stop band above the first pinned mode is therefore highly dependent on rail pad dynamics. The pinned mode typically lies above 1000 Hz.

At higher frequencies cross section deformations of the rail start to exhibit.
The formulas given above are approximations to demonstrate the interdependencies.

2.2.5 Track decay rate (TDR)

Experimentally the effective length of the radiating rail in dependence of the frequency of the excitation is determined from the track decay rate, which describes the decrease in amplitude of the vibration along the rail. The internal damping of the rail itself is low. The most important track element for the damping of higher frequencies in the rail is the rail fastening, which includes the rail pad with its elastic properties and the resilient fixation that couples the rail to the sleeper.

2.2.6 Radiation

All track components with a substantial surface area may contribute to the noise emitted directly, if their surfaces are excited to vibrate in the corresponding frequency range. Thereby the noise emitted by a track component is related to the size of the vibrating surface, the vibration velocity of the vibrating surface and the radiation ratio. The latter equals one if the wavelength of the vibration is smaller or equal to the size of the radiating object. Where the wavelength is far larger than the size of the vibrating surface the radiation ratio tends to zero. From these conditions it follows that the direct noise radiated from a track is dominated by frequencies above 300 Hz.

2.3 Ground vibrations

2.3.1 Excitation

Ground-borne noise and vibrations are generated at the wheel/rail interface either from a passing load (boogie, axle and wheel) at low frequencies, from parametric excitations such as the varying stiffness due to a discretely supported rail, from larger defects and irregularities on the rail, loose rail fasteners /"hanging"(=unsupported) sleepers or defects in the wheel running surface (wheel flats or wheel out of roundness leading to dynamic excitation) or from the unbalanced wheel mass. Car bogie or car body bounces may be responsible for the very low frequency vibrations.

2.3.2 Track resonance

The track resonance frequency $f_{v/t}$ is determined by the unsprung mass m_u of the rail and the (dynamic) track stiffness k_t' of the entire track superstructure

$$f_{v/t} \approx \frac{1}{2\pi}\sqrt{\frac{k_t'}{m_u}}$$

The track resonance marks the frequency above which parts of the track masses become dynamically isolated in relation to the ground. Higher frequencies are more confined in the track system where they may propagate along the track in much the same way as waves are free to propagate in the rail above the rail resonance. All mitigation measures against ground vibrations applied within the track superstructure will aim to lower the track stiffness k_t' to shift the track resonance to lower frequencies. The resultant effect will be most notable at the frequency of the resonance that occurred before the lowering of the track stiffness. Frequencies below the track resonance frequency can only be attenuated by secondary measures in the transmission path through the ground.

2.3.3 Soil Damping

Ground vibrations are formed from the displacements transmitted through the track superstructure. Ground vibrations travel in mainly three wave forms (i.e. pressure waves, shear waves and surface (Rayleigh) waves) with different propagation speeds and different wavelengths. Shear waves and Rayleigh waves are dispersive, i.e. the propagation speed changes with frequency. Diffraction (bending) and reflection may occur at intersections between different soil layers. As the soil being the transmitting media has a damping that takes away a portion of the vibration per cycle, the higher frequency vibrations decay faster over distance.

2.4 RAMS (Reliability / Availability, Maintainability and Safety)

This section explains the terminology and definitions for the terms associated with the commonly used abbreviation RAMS.

2.4.1 Reliability

Reliability is defined as the probability that an item can perform a required function under given conditions for a given time interval.

2.4.2 Availability

Availability is defined as the ability of a product to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval assuming that the required external resources are provided.

2.4.3 Maintainability

Maintainability is defined as the probability that a given active maintenance action, for an item under given conditions of use can be carried out within a stated time interval when the maintenance is performed under stated conditions and using stated procedures and resources.

The following terms are related to maintainability:

2.4.3.1 Maintenance

The combination of all technical and administrative actions, including supervision actions, intended to retain a product/item in, or restore it to, a state in which it can perform a required function.

2.4.3.2 Predictive maintenance

In predictive maintenance, one predicts the moment in time when a failure criterion will be exceeded; the maintenance actions are then planned and carried out before that moment. This prediction is made with a predictive model that is fed by historical and empirical (track) inspection data.

2.4.3.3 Preventive maintenance

The maintenance carried out at pre-determined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of a product/item.

2.4.3.4 Corrective maintenance

The maintenance carried out to repair a failure or defect in the ‘system’, which occurred before its likely occurrence was detected and corrected during preventive maintenance – or passed unnoticed at inspection or planned maintenance. This also includes maintenance measures necessary as a consequence of failure in another system that caused damage (e.g. maintenance to the track as a result of derailment due to vehicle failure).

2.4.3.5 Inspection

Check for conformity by measuring, observing, testing or gauging the relevant characteristics of a product/item.

2.4.4 Safety

Safety is defined as the state of a technical system being free from unacceptable risk of harm.

2.4.4.1 Risk

Risk is defined as the probable rate of occurrence of a hazard causing harm and the degree of severity of that harm. As a combined effect it is important to consider the probability that a hazard actually leads to harm (the rate of occurrence of accidents and incidents resulting in harm (either caused by a hazard or otherwise) and the degree of severity of that harm. Mathematically this is represented as:

Risk = Rate (of accidents) x Degree of Severity (of harm)

2.4.5 The Swiss practice

The RAMS concepts are rather abstract concepts. Therefore they require a more concrete and practical interpretation. Below, the interpretation given to the RAMS elements in the practice of Swiss railways is presented.

2.4.5.1 Reliability and availability

Reliability is related to the number of incidents resulting in delay. This figure itself is related to the MTBF (**M**ean **T**ime **B**etween **F**ailures) or rather the MTBSAF (**M**ean **T**ime **B**etween **S**ervice **A**ffecting **F**ailures). The latter takes into account whether the train service is affected while the MTBF takes into account all kind of failures of a component.

Availability is related to the time that a certain asset is not available. This is called unavailability and a key figure is the ratio of:

$$\frac{\text{train delay minutes}}{\text{milion route kilometers}}$$

SBB’s aim for availability is to have a high score on customer punctuality. To accomplish that, a classification for traffic corridors based on operational usage has been proposed. This is a quantification that takes into account the number of trains per day and corrects this classification for the number of train paths per day and the availability of backup routes.
In practice, all main corridors (‘Hauptstrecken’) normally have backup routes. The secondary corridors (‘Nebenstrecken’) do not. It is not monitored (directly) when a backup route is taken instead of the normal route, but it will show up in the unavailability ratio whenever a train is delayed due to it taking the backup route.

2.4.5.2 Maintainability

The maintainability is related to the time that an asset is out of service or the mean time to repair. This time comprises the repair time and the time it takes to start the repair (intervention time).

2.4.5.3 Safety

Derailment is the main safety risk which is influenced by the track. SBB collects data about derailments in a database. No measure for safety is used yet so we propose to use the **M**ean **T**ime **B**etween **S**afety **S**ystem **F**ailure (MTBSSF) as indicator.

2.5 LCC (Life Cycle Costs)

Life Cycle Costs (LCC) analysis is a method for calculating the total cost of a system or a product over its total lifespan. It is a systematic process to quantify and evaluate cost impacts. The outcome of an LCC assessment can be used as the cost side of a cost benefit analysis and thus supports decision making through economic assessment and comparison of alternative strategies and designs. For railway infrastructure managers, the cost includes the following parts:

- Procurement (including installation);
- Operation;
- Maintenance;
- Non-Availability;
- Social Economics;
- Demolition and removal.

2.5.1 Swiss practice

To calculate the LCC of design variants, SBB uses an Excel tool. In this tool, the following cost component groups are considered:

- Investments & renewal;
- Preservation (monitoring, maintenance, refurbishment, troubleshooting);
- Other (asset management, costs of other assets, earnings).

These costs are put in for each year that they are made, either as fixed costs or costs per meter of the asset or per hour for monitoring and maintenance. The figures for these costs are supplied by the purchasing department of SBB.

The costs do include the procurement, operation and maintenance costs. These are generally considered as the direct costs. The indirect costs (costs of non-availability and social economic costs including person hours) are not considered.

2.6 Description of methods for an optimization strategy

Methods for optimization are applied not only to support the decision making, but also to document the process leading to the decision and to support an objective decision.

2.6.1 Cost Benefit Analysis

Cost Benefit Analysis (CBA) is a method for decision making through economic assessment and comparison of alternative strategies and designs. It assesses both the benefits and the costs of certain interference. The ratios of benefits to cost of different options help to rank the options according to the best benefits to the same costs, or, alternatively, the lowest cost for the same benefits. The method assesses whether or not a certain intervention is cost efficient by direct comparison of costs and benefits (provided that both are expressed in monetary terms). For impacts such as noise and vibration, where the objective is to reach a limit value, the problem is often to find the solution that provides the necessary reduction to the lowest cost. The ratios are best expressed as non-dimensional, which requires the benefits to be expressed in the same dimensions as the cost, i.e. preferably in monetary units (e.g. CHF). Relevant information on what is called the "valuation" of environmental noise was collected in the last two decades, allowing a cost benefit analysis for various noise mitigation measures. There is a reasonable consensus about the monetarization of noise benefits. For vibration, there is no consistent valuation available yet.

For the cost side, often the LCC (see above) is taken as the decisive quantity, but for noise mitigation measures life cycle costs are neither generally available nor systematically collected. This is even more so the case for vibration mitigation.

For railways, the cost side might also be approached as the sum of the RAMS elements (see above), which leads to a more generic outcome. RAMS elements are more and more available and collected.

2.6.2 Multi Criteria Decision Aiding

Multi Criteria Decision Aiding (MCDA) is a method to identify the preferable solution from a series of proposed solutions. Essential to the method is the definition of a set of decision criteria. The set should include all (or at least most) of the criteria that are considered crucial for the decision. Very often cost is one of these. The advantage is that there is no need for uniform dimensions (criteria can be dimensionless or even qualitative only) and different criteria can be weighted to allow a differentiation of their relevance. A 2010 paper by NASA compares three different MCDA methods (Pugh, Analytic Hierarchy Process and Kepner-Tregoe) on the basis of their accuracy and the amount of data and time needed. For riskier decisions it is recommended to involve higher level stakeholders to choose an optimal decision.

2.6.3 Stochastic Multi Criteria Acceptability Analysis

SMAA or Stochastic Multi Criteria Acceptability Analysis is a specific form of MCDA, which allows expressing the values for different criteria in a probabilistic way. It is particularly suited for situations where there is uncertainty about the value of certain parameters. It takes into account the uncertainties and assesses the acceptability and the level of confidence of the outcome and the so-called central weight factor applied by the decision makers involved. The method is more mathematical than the MCDA and as a consequence is less inviting to those involved in the decision making to start a dialogue.

2.6.4 Comparison between CBA and MCDA

	CBA	MCDA	SMAA
Strengths	- Direct comparison between costs and benefits in the same familiar unit - Consistent and transparent Highly suitable to support go/no go decisions	- Any criterion can be included and quantified - Sensitivity analysis is relatively easy; allows for evaluation of the accuracy of results - Allows public participation and democratic decision making - Allows emphasis on certain aspects	- Allows for probabilistic approach, taking account of uncertainties in parameters - Deals with uncertainties in parameters
weaknesses	-Monetarization is needed: criteria can only be taken into account if they can be monetarized (unless one uses the equal impact method) -Monetarization is difficult for some criteria due to the lack of data - Ethical objections against monetarization of health effects may exist	- It is not a generic method: In each situation, it requires development and tailoring of weighting factors - The method is less known: this may make it more difficult to explain the method and the results of it	- Method is less transparent and not directly comprehensible - Evaluation may require the involvement of an analyst More mathematical, hence less consensus building

Which method is to be preferred will depend on the situation. CBA is more suitable for policy making, which is generally a large-scale or (inter)national issue, for instance when one wants to know what the costs and the benefits are of changing the sleeper type for the whole rail network in Switzerland. CBA will lead to less discussion about the method and the results, if based on valid evidence from monetarization research, and will generally be understood and accepted. Direct public involvement into the method is not very common for policy making on a national scale; public involvement is executed indirectly, through democracy.

MCDA is more suitable for a local situation, e.g. at a local noise hot spot. The MCDA can be tailored to the specific situation and the specific public environment, e.g. by adding locally relevant criteria. If used well it may increase the acceptance and public feeling of having an influence on the own situation. MDCA also enables the relatively easy incorporation of ‘softer’

criteria and arguments (aesthetics, socio-cultural aspects) which are hard to monetarize in the CBA approach, but which may be important for the public opinion and acceptance.
SMAA is a more scientific and mathematical method, allowing for decision aiding in situations with very little reliable information about the exact value of the parameters. It is a more developed variation of MCDA.

Phase 1 of Go-Leise has given examples of how CBA and MCDA approaches could be applied.

3

Impact of mitigation measures and exchange of track components

In this chapter the most important results from the literature research and expert interviews are listed in the form of impact tables for track components or track (sub-) systems. The impact of a change in the track system is considered for a straight track without singularities such as joints and switches. All impact entries in the following tables are expressed in reference to the nomenclature of the Introduction and common terminology.

To score the effects we use the 3x scale (0, 1, 3, 9, 27). If there is no effect the score is 0, the score is 27 for a major effect. The sign (+ or -) denotes if the effect is positive or negative in the sense of achieving the envisaged goal. The score and sign are added in brackets. Where the effect is unknown the score is [+/-] while no number is given if the strength of that effect is yet undetermined. The effect on noise and vibrations is also denoted in decibels and wherever applicable the frequency range where the effect takes place is given.
The components listed are examples. Other changes or innovations in components could be considered in the same way. The scores presented in the examples are based on the current knowledge of the effects. Further research and experiments may lead to a change of insight which is likely to affect the scores.

3.1.1 Rail grinding

Considerations: Used to (re)shape the rail head; prevent/correct corrugation and RCF damage; as a side result the acoustic roughness is reduced; optimal wheel rail contact will increase lifetime of both the wheel and the rail.

	RA	M	S	LCC	Noise	Ground vibrations
	MTBM decreases [3-] MTB(C)F increases [9+] Grinding debris causes signaling failure [3-]	No influence [0]	Prevent head-checks [9+] Prevention of corrugation removes the risk of fastener failure [3/9+]	More grinding: Increase preventive maintenance costs [3-] Decrease corrective maintenance costs due to head checks and fastener failure [9+]	If overall roughness is lowered (i.e. in the case of rolling stock with smooth wheels) the noise radiation will be less Grinding marks can temporarily increase noise! [3-] In the well maintained Swiss rail networks the benefits from acoustic grinding are 2-3 dB [9+] If otherwise corrugation existed [27+]	If overall roughness and rail head defects are less ground vibrations in the (less important) higher frequency range decrease likewise. [+]

Remarks: If corrugation is prevented that otherwise would have grown the noise benefit can be much higher (10-20 dB)

3.1.2 Rail dampers

Considerations: Increase track decay rate to reduce rolling noise emission from the rail

	RA	M	S	LCC	Noise	Ground vibrations
	No influence on vehicle bearing function [0]	Inspection is more difficult. Dampers need to be removed for welding, rail replacement MTTM increases [9-]	Track diagnostics more difficult [9 -]. Rail dampers coming loose may affect safety [1-].	Higher capital costs [9-] Higher maintenance costs due to shorter? MTTM [1-]	Insertion losses varied over the different investigating studies: 2-4 dB 2.5 dB 0.7-1.5 dB [3+] In CH only effective in B70 sleeper system or in situations with soft rail pads (the latter currently only on the NBS line and not noise relevant). [9+] Impact of rail dampers is found to be low if TDR was initially high (In CH TDR is high in most cases thanks to stiff rail pads) [1+]	Rail dampers have next to no impact on ground vibrations [0]

Remarks: Rail dampers are installed to damp rail vibrations above the rail resonance. Rail dampers change the rail modes (pinned-pinned mode) and add new ones. They also increase rail mass and lower the rail resonance frequency (increases noise up to former resonance frequency). Note: SBB tested rail dampers for several years and currently does not recommend their use.

3.1.3 Under sleeper pads

Considerations: Protect ballast, decouple track system from environment: Ground-borne noise reduction in limited and less important frequency range (appr. > 50 Hz)/compensation of locally inhomogeneous conditions: e.g. transitions between different construction types, between embankment and bridges as well as at level-crossings. Reduction of long pitch corrugation in narrow radius curves.

	RA	M	S	LCC	Noise	Ground vibrations
	MTBM decreases so availability increases [3+]	No influence because USP is made a little smaller than the sleeper itself to avoid tamping problems [0]	No influence, or increased side stability [0/1+]	Higher capital costs (AT: 740 versus 700 euro/m for track renewal) [1-] Lower maintenance costs, increase MTBM (tamping cycle is doubled), service life is 25% more [9+] Lifetime of USP is still unknown since they have not been applied for a very long time yet [+/-]	Increase in noise emissions by 1 to 4 dB largely in the 200 to 1000 Hz frequency range [3-]	Reduction up to 20 dB above the vehicle on track resonance frequency [9+] Often increase in ground-borne vibrations below vehicle on track resonance frequency [1-]

Remarks: Tamping intervention cycles may increase in the transition zone. Inconsistent findings on lateral track resistance

3.1.4 Stiff rail pads

Considerations: Less noise/increased ground vibrations; higher lateral rail stiffness

RA	M	S	LCC	Noise	Ground vibrations
MTBF decreases [3-]	No influence [0]	Higher lateral rail stiffness [3+]	Hard rail pads have longer lifetimes [3+] Higher stress on sleeper [3-]	Hard pads most notably lower the noise in the frequency range 300-1600 Hz (increased TDR) Noise decrease of approximately 2-5 dB [9+]	With harder pads more vibrational energy is transferred into sleepers and ballast Insertion gain of 5-15 dB in frequency range (60-200 Hz) [3-]

Remarks: Rail pad stiffness determines the rail resonance frequency. Rail pad dynamic stiffness changes with: Static stiffness (linear), Load (increase), Frequency (increase), Temperature (decrease), Age (?). Note: Stiff rail pads are current practice on the SBB network.

3.1.5 Soft rail pads

Considerations: More noise/less ground vibrations; higher on vehicle comfort; protection of sleeper

RA	M	S	LCC	Noise	Ground vibrations
MTBF increases [3+]	No influence [0]	Softer pads allow more lateral movement of the rail [3-]	Reduction of track component/sleeper damage: longer sleeper lifetime [3+] softer pads have shorter lifetime [3-]	Soft pads shift the rail resonance to lower frequencies thereby enhancing noise Increase in noise between 500 Hz and 2 kHz by 2-5 dB [9-]	Insertion losses of 5-15 dB in limited frequency range (60-200 Hz) [3+] Below the vehicle on track resonance frequency the Ground vibrations were enhanced! [1-]

Remarks: Rail pad stiffness determines the rail resonance frequency. Rail pad dynamic stiffness changes with: Static stiffness (linear), Load (increase), Frequency (increase), Temperature (decrease), Age (?). Note: Stiff rail pads are current practice on the SBB network.

3.1.6 Rail pad damping

Considerations: Increases track decay rate; difficult to adjust as an individual parameter

RA	M	S	LCC	Noise	Ground vibrations
No influence [0]	No influence [0]	No influence [0]	May be difficult to achieve without affecting stiffness Reduced lifetime (in curves) [-]	Numerical results show an improved situation for noise with higher damped rail pads [+]	Higher damping should also benefit the mitigation of Ground vibrations [+]

Remarks: Dynamic stiffness increases with damping. Damping is effective for vibrational modes of the rail with displacements at the rail seat. Longitudinal shearing modes of the rail wear the rail pad.

3.1.7 Enlarged (heavier) rail profile

Considerations: Heavier profile for larger axle loads and/or traffic intensity; higher rail stiffness means less amplitude in the vibrations (partially compensated by enlarged surface area). Higher mass lowers second cut-on frequency.

RA	M	S	LCC	Noise	Ground vibrations
MTBCF increases [3+]	Change of equipment on a line with mixed profiles [1-]	Margin for lifetime, resistance against fatigue [3+]	Higher capital costs [3-] Longer life and higher availability when applied at same traffic intensity [9+]	Comparison of VA71b to UIC 60E1 resulted in average reduction of 1.5 dB [1+]	Higher impedance of track and less displacement in the soil [+]

Remarks: Test did not just change the rail profile, but also the rail pads. The true effect may therefore be uncertain.

3.1.8 Hardened rail head

Considerations: Intrinsic resistance against RCF damage, rail hardening reduces the roughness growth rate so low roughness remained longer

RA	M	S	LCC	Noise	Ground vibrations
Larger stress resistance: MTBF increases [9+]	May affect ease of welding and hence MTTM [1-]	Postpone and/or reduce growth rate of head-checks [9+]	Higher capital costs [9/3-] Decrease preventive and corrective maintenance costs and increased lifetime [3/9+]	Comparison of VA71b to UIC 60E1 resulted in average reduction of 1.5 dB [1+]	Less rail head defects and overall roughness reduce Ground vibrations [+]

Remarks: Longer grinding times required and grinding marks don’t wear off as fast

3.1.9 Resilient direct rail fastening

Considerations: Less coupling to the sleeper, therefore lower ground vibrations but more noise due to deceased rail decay rate.

	RA	M	S	LCC	Noise	Ground vibrations
	MTBF lower than for conventional fasteners [-]	Special machines required for maintenance [3-]	No influence [0]	Higher capital costs [3-] Lifetime effects unknown [+/-]	Less damping of the rail as there is no additional rail pad Low rail resonance frequency [-]	Pandrol Vanguard system was found to have an insertion loss of 5-10 dB above 40 Hz for metro type trains [3+]

Remarks: High preload fastening systems show better TDR results and should have less noise.

3.1.10 Mono-block concrete sleepers

Considerations: Mono-block sleepers help to keep the gauge; less ballast crushing as with bi-block sleepers; stiffer than wooden sleepers; High concrete mass lowers sleeper resonance thereby enlarging stop band up to the rail resonance. Prolonged lifetime and higher load capacity versus wooden sleepers

	RA	M	S	LCC	Noise	Ground vibrations
	MTBF is better [+]	Wooden sleepers allow repairing, concrete is not repairable [3-]	More stable track system [3+] no fire hazard [3+]	Lower capital costs [+] In general longer lifetime [+] Quicker ballast degradation, requiring more frequent tamping [-] Sleeper itself requires less maintenance [+]	Decreased noise in the frequency range 200-700 Hz by 2-5 dB versus wooden sleepers Enlarged stop band (TDR) between sleeper resonance and rail resonance [3+]	Higher mass than wooden sleepers therefore lower track resonance frequency and decreased ground-borne noise [+]

Remarks: Mono-block sleepers exhibit modes that make the two rails a coupled system (with n-phase and anti-phase modes) Note: Mono-block concrete sleepers are the most common sleeper type in noisy areas. Bi-block sleepers are rare in Switzerland.

3.1.11 Mono-block wooden sleepers

Considerations: More flexible and resilient than concrete sleepers (no rail pads required); Cheaper but with a shorter lifespan; Less fragile to critical failure; repairable

	RA	M	S	LCC	Noise	Ground vibrations
	undetermined	*undetermined*	*undetermined*	Side stability is lower due to lower weight. Rail buckles out [3-]	Increased noise in the frequency range 200-700 Hz by 2-5 dB versus concrete sleepers Higher vibration amplitude on sleeper means higher noise radiation 3 dB higher noise than with bi-block sleepers [3-]	Lower mass than concrete sleepers therefore higher track resonance frequency and increased ground-borne noise [-]

Remarks: none

3.1.12 Mono-block wide concrete sleepers

Considerations: Less ballast crushing than standard concrete sleepers; higher axle loads; better stress distribution on ballast

	RA	M	S	LCC	Noise	Ground vibrations
	undetermined	Tamping might be hindered or use of specific tamping machines is necessary [-]	*undetermined*	Higher capital costs [-] When resulting in greater stability, less tamping is required [+]	B06 wide sleepers are comparable to wooden sleepers, if they are combined with stiff pads [3-]	B06 wide sleepers had overall higher ground vibrations; up to 10 dB in the frequency range below 20 Hz and above 80 Hz compared to wooden sleepers [1-]

Remarks: The increase in ground vibrations from wide concrete sleepers above 80 Hz in comparison to wooden sleepers is likely due to a higher track resonance frequency.

3.1.13 Increased ballast depth

Considerations: Decrease vibration propagation, increase sound absorption? Increased mass will shift track resonance frequency in combination with UBM

	RA	M	S	LCC	Noise	Ground vibrations
	More settlement due to movement of the ballast in horizontal direction, MTBF decreases [-]	*undetermined*	*undetermined*	Higher capital costs [-] More ground usage [-]	A net mitigation in the form of a change in absorption due to a frequency shift was found for increased ballast depth from rescaled laboratory measurements in a reverberation chamber [1+]	More resilience from ballast bed reduces track resonance frequency and lowers ground vibrations [+]

Remarks: none

3.1.14 Under ballast mats (UBM)

Considerations: Applied in situations where the substructure is rather stiff; Isolation of ground vibrations; Protection of surroundings against vibrations; Reduction of secondary air-borne noise of bridge structures; requires side support of ballast; reduces track degeneration by preventing settlement

RA	M	S	LCC	Noise	Ground vibrations
No influence for the track system itself [0] More maintenance in transition zones [1-]	No influence [0]	Allegedly reduced ballast stability without side support [0/1-] can be altered also by ballast mat geometry design [0]	Higher capital costs (also due to side support) [9-] Reduction of ballast depth in tunnels and on bridges/viaducts [3+] Reduction of ballast degradation and hence ballast maintenance [+]	No influence [0]	Insertion losses of 5-10 dB for frequencies larger than 30 Hz [3+] At times an insertion gain is seen at the new track resonance frequency!

Remarks: In comparison to USP and soft rail pads the UBM is able to suspend (dynamically isolate) larger part of the mass in the track system

3.1.15 Soil improvement

Considerations: Improve stability so good track alignment is maintained longer

RA	M	S	LCC	Noise	Ground vibrations
No influence if tamping is done outside period of availability [0], otherwise a slight positive effect [1+] Remove speed restriction for badly drained zones [9+]	No influence [0]	No to little positive influence [1+]	Higher capital costs [new track: 3-, existing track: 27-] Maintained track stability reduces maintenance costs [+]	No impact as long as track stability is maintained [0]	Numerical examinations suggest that subgrade stiffening or a wave impeding block can give insertion losses of 5-10 dB. [+]

Remarks: none

4

Important knowledge gaps

Just as important as the listing of the literature findings and expert knowledge is the identification of the knowledge gaps. We found that the knowledge gaps could be ordered in three categories which are described next.
The first category includes all missing and uncertain knowledge regarding the performance and interdependency of optimizations done on the basis of changing individual track components.
The second category relates to knowledge gaps in the overall track optimization.
While the first two categories describe the lack of knowledge for optimizing a given situation with the tools already available to us, the third category reflects the missing potential in the optimization process towards the optimum. As this may include yet undeveloped track components, layouts and services the number of knowledge gaps in this category is infinite. Nonetheless, listing ideas and theories here helps future designs of computational modeling, laboratory experiments and field tests that may proof just as valuable for an overall optimization as the filling of knowledge gaps for existing systems.

From the complete compilation of knowledge gaps identified from the literature study, expert interviews, the Go-Leise workshop and internal discussions within the group of the consortium members and SBB a shortlist of important knowledge gaps was drafted. The decision process for obtaining the most important knowledge gaps was achieved by raising a vote in a group of experts for a number of subclasses of knowledge gaps. The subclasses where formed of five sets of knowledge gaps related to a specific track component and the three other sections of knowledge gaps. In a first step the five track components with the strongest impact on all of the Go-Leise parameters RAMS, LCC, noise and vibrations were chosen in a voting to be

- Rail roughness
- Under sleeper pads
- Rail pad
- Rail fastening system
- Sleeper

For all of those a poll was held to identify the corresponding most important knowledge gap, as was also done for the knowledge gaps regarding data collection and optimization, statistics and designing of experiments and new/innovative ideas.

The knowledge gaps identified this way are part of the very basis for next steps in the Go-Leise project. It stands clear that the gaps chosen from a vote will not necessarily form the complete set of gaps to be filled to proceed with an optimization, but rather a starting point from where to evolve the holistic optimization approach.

In the following all the selected gaps are shortly addressed with the aim to clarify what the actual gap is, which milestones are to be reached in order to fill the gap and what approaches may be used for it. In terms of an estimated time and money requirement they are rated as:

- Low: half a year, less than CHF 100’000
- Medium: One year, less than CHF 500’000
- High: 1 – 3 year, less than CHF 1’000’000
- Very high: More than 3 years, more than CHF 1’000’000

There is also a short proposal for actions and next steps to be taken.

4.1 Rail grinding

4.1.1 Roughness monitoring

From 2020 a rail roughness monitoring system will be implemented by SBB. This is a legal obligation under the revised Bundesgesetz zur Lärmsanierung der Eisenbahnen (Federal law on the noise mitigation of railways). This system will represent an important contribution to the optimization of the grinding strategies and methods of the Swiss railway network. The optimization might be in terms of grinding speed, frequency, cycles, rotational or longitudinal grinding etc. The system is expected to deliver data on the variance of rail roughness achieved along a larger rail section. So far, this was deemed an uncertainty that could possibly be come by from a monitoring of rail roughness in noise hot spots or even the entire railway network. As to measuring the roughness in a monitoring system it was agreed upon that the impact of the variance of the roughness across and along the rail head should be taken into account in particular on lines with mixed traffic.

Rail roughness monitoring is already being practiced i.e. in the Netherlands as well as in Germany. The monitoring thereby is obtained from measuring of a roughness related property (such as noise or axle accelerations) from a moving test vehicle and assuming a direct proportionality to the roughness profile of the rail running surface at any time. If the functional relation between this measured property and the contributions from the rail roughness to the total effective roughness is approximately the same for all sorts of track conditions (yet similar track design) the method may be calibrated to yield approximate roughness values. The obtained quantity is the roughness relation to the actual wheel/rail contact for the test vehicle. If the rail roughness strongly differentiates across the rail head, the results may be different for different test vehicles, running speeds and wheel conditions.

To finally arrive at an optimal grinding strategy different grinding methods (conventional grinding with a rail head smoothening finish as well as acoustic grinding) should be tested and comprehensively compared to each other. Grinding companies should be involved to optimize this process for the specific SBB requirements. As different parts of the network will demand different degrees of treatment due to being in a more or less noise sensitive surrounding, the overall optimization in the network could be done on the basis of RAMS and LCC values.

Suggested actions: Initiate a rail roughness monitoring pilot project, where different monitoring possibilities are compared and calibrated for different situations. Together with point 5.1.2 determine an optimal grinding strategy, taking RAMS and LCC into account.

Cost/time requirement: Cost low, time high

4.1.2 Roughness growth rates

The roughness growth rate stands out as *the* determining parameter to the optimization of the grinding strategy. The mechanisms that drive the roughness growth rates are still not fully understood, partially due to a lack of complete and reliable data. It could therefore become necessary to look at roughness growth rates in the SBB network and look for dependencies on axle load, type of traffic, speed, track dynamics and materials etc. If relations can be drawn it could become possible to transfer the strategy from one location to other parts in the railway network without having to go through the tedious process of the optimization again.

To obtain complete and reliable data it may be necessary to not just measure the rail roughness in test sections but also to record all possibly related parameters (all traffic related ones such as speed, load, type of traffic, wheel conditions etc. as well as track related ones such as track dynamics and stiffness of pads, ballast, soil or even the condition of the rail fastening). These measurements should be done over a timeframe of several years, where the same locations are measured in regular intervals. A similar project was conducted in the Netherlands in the (rather far) past. The set up and results of this study can be used as a blue print.

Suggested actions: Initiate a rail roughness monitoring project as suggested in 4.1.1. To derive dependencies choose a number test sections at which additional parameters are determined.

Cost/time requirement: Cost medium, time high to very high

4.2 Under sleeper pads (USP)

4.2.1 Cause of noise increase with USP

The installation of under sleeper pads is often the cheapest by far of all mitigation measures for ground-borne noise and vibrations. However, tests with (soft) USP in the SBB network showed a clear increase in airborne noise, whereby the cause of this noise increases is as yet undetermined. By far the largest hot spots for ground-borne noise and vibrations are also sensitive to airborne noise and hence a noise increase without additional mitigation is often inacceptable. Explaining the root of the increased noise emissions will help to design reliable and cost effective counter measures for vibrations.

Tests with USP in the Swiss railway network could be repeated recording additional information such as sleeper and rail vibrations and TDR alongside the ground vibrations and noise. Ideally this is done for a large variety of USP (different stiffness, damping and track configurations) and at several locations to rule out dependencies from hidden local parameters. It should then also be studied how the USP performance is affected by the other resilient track elements (mainly the rail pad). If indeed the change in support stiffness for the sleeper causes an increase of its excitation (either in amplitude or by shifting the frequencies of dominant sleeper modes), possible measures would have to be focused on the sleeper surface area that radiates the noise (i.e. change of sleeper surface profile, covering of the surface, damping of the sleeper etc.) or on trying to optimize the supporting stiffness configuration of rail pad, USP and ballast stiffness (i.e. by having softer rail pads and harder USP – although the softer rail pads may increase noise contributions from the rail as it shifts the rail resonance frequencies to lower frequencies).

Suggested actions: Set up test tracks with various USP sections and reference sections. Measurement of noise and ground vibrations alongside velocity levels on the sleepers. Different configurations of USP and rail pad stiffness (and damping) should be tested. In parallel some advanced noise calculation model could be used to first quantify the validity of its predictions with USP and then perform a full parametric study to narrow down the number of configurations to the most promising ones.

Cost/time requirement: Cost medium, time medium (high with LCC)

4.3 Rail pad

4.3.1 Characteristic rail pad properties and their determination

The rail pad is a key component to track dynamics. It has a certain characteristic behavior when built into a track system which it mainly draws from its dynamic stiffness and damping properties. However, these properties are not intrinsically bound to the rail pad but will change with thickness, size, material composition, design, preload, axle load, temperature, frequency of the excitation and possibly age. It is therefore important to standardize the test procedure for rail pads in a way that their predetermined characteristic properties (such as dynamic stiffness and damping) relate to their performance in the track.

As different laboratory testing methods exist to determine dynamic stiffness and damping of a rail pad the variance of the test procedure and viability of test setups should be investigated. Ultimately only testing methods and procedures should be used that are guaranteed to give comparable results. In parallel an indirect determination of the elastic decoupling of rail and sleeper could be aimed at for in situ measurements (i.e. by determining transfer functions from rail foot to seat on the sleeper and average surface vibrations along the rail web foot and head). The development of an in situ method has the benefit of being relatable to the actual track performance and the operational state may more easily be mimicked. In particular the loaded track situation could be tested either with an excitation from train pass-byes or from force excitations in conjunction with a parked train. However, the relation of the measured parameters to the properties of only the rail pad would then have to be evaluated versus laboratory tests, as there will likely be other factors (such as the rail fastening resilience, preload etc.) playing a role in the in situ measurements. Any relations that can reliably be drawn between a standardized laboratory testing and in situ performance will significantly improve the communications with rail pad manufacturers, as requirements may clearly be formulated and future rail pad developments are given a goal.

Suggested actions: Step 1: Setup a laboratory test campaign to determine static/dynamic stiffness and damping (e.g. according to ISO 10846). See how comparable results are and how they match with manufacturer information. Step 2: Initiate test track measurements with different rail pads and relate laboratory results to field test by comparing TDR but also transmission losses to the sleeper. As preload may have a severe impact on the results, in-situ measurements may have to be done with a standing train that loads the track. This project should include an assessment method for the impacts of different rail pads on RAMS and LCC.

Cost/time requirement: Step 1: Cost medium, time medium. Step 2: Cost high, time high

4.3.2 Load and frequency dependent stiffness design

To improve ground-borne noise and vibrations and noise likewise it would be beneficial if the stiffness of a rail pad were designed to be frequency dependent and (inversely) load dependent. Moreover a low stiffness at low frequencies would be desirable to mitigate ground vibrations and a high stiffness at high frequencies for a high rail resonance and a good structural damping of the rail should be aimed for together with low stiffening under load.

The required frequency characteristic is already being obtained in standard rail pad materials and designs as dynamic stiffness generally increases with frequency however the potential is likely not exhaustively explored. The main factor in this stiffening at higher frequency cyclic loading is the damping (or loss factor); it could therefore be beneficial to have more resilient pad materials and larger contact areas to rail and sleeper alongside a high intrinsic damping of the material (effective damping scales with the volume of material under displacement).

From this perspective a design of softer rail pads from hard pad materials and limited contact areas is not ideal. Geometric designs should focus on optimizing heat transfer (for longer durability of the pad), low overall load response and high damping ratios. Entirely new material (new to the railway sector) could be tested in the process.

Suggested actions: Setup a project to develop an optimized rail pad possibly using new materials and/or a new designs using the approaches defined in 4.3.1. This project should include an assessment method for the impacts of different elastic properties on RAMS and LCC. It is questionable whether such a project could be set up, as it would require manufacturers to be involved. Given their commercial interests these would only be willing to collaborate as far as the project has a pre-competitive character and outcome.

Cost/time requirement: Cost very high, time very high

4.4 Rail fastening

4.4.1 Ideal dimensions of the rail fastening

The rail fastening system keeps the rail and sleeper coupled, prevents rail roll and may also add resilience in lateral direction. If the fastening cannot keep the rail and rail seat on the sleeper in parallel the performance of the rail pad is diminished (the same would be true for abrasion of the rail seat). The dimension of the fastening system may therefore play a role and particularly if larger sized rail pads should be tested (i.e. on wide sleepers) the number of fixation points should be increased. If a loss in stiffness from reduced contact area of rail and sleeper turns out to be important, the rail fastening / rail pad systems ability to compensate sleeper mode excitation may also be crucial.

Suggested actions: Start a project in which the fastening system is optimized and tested. This can include using new materials and changes in the design. With respect to the participation of manufacturers see remark in the previous section.

Cost/time requirement: Cost very high, time very high

4.5 Sleeper

4.5.1 Characteristic sleeper properties

The main characteristic property of a sleeper is its mass in the simplified models for rail noise and vibrations. Additionally the sleeper has a shape that plays a role in the noise radiation from the sleeper itself, a bending stiffness that determines its modes and a damping. Generally the sleeper contribution to the track noise is disregarded above the rail resonance. In the factor X project however, a strong correlation of track performance (track decay rate) to the sleeper type (B70/B91) was found. Although the mechanisms that cause the difference in track decay rate are largely undetermined, a possible cause may lay in the coupling of the track to the sleeper dynamics (modes) above the pinned-pinned frequency. As both sleeper types have almost similar weight and designs, one should also look at additional properties such as prestress and structural damping for future comparisons with different sleeper types. Testing for sleeper modes in the track is possible via acceleration sensors, whilst construction based properties should be asked for from the manufacturer.

A new sleeper design should be constructed such that it ideally has a high internal damping although this may require new sleeper shapes, materials and/or a layered construction. If a combined (layered) construction is chosen, some of the elastic properties of the rail pad and USP could be transferred to the sleeper. Its vertical dynamic stiffness should then again be low at low frequencies and high at higher frequencies.

Suggested actions: Step 1: Setup a test campaign to compare vibration levels (displacements) on available sleepers in a comparable track surrounding. Testing may be done in-situ from train pass-byes and hammer excitation. Compare to dynamics of isolated sleeper and see if dependencies can be drawn to pre-stress, age, etc. Step 2: Project in which new sleeper designs are developed and tested.

Cost/time requirement: Step 1 Cost medium, time medium. Step 2: Cost very high, time very high

4.6 Data collection and optimization

4.6.1 RAMS and LCC data collection

There is limited historical data available particularly for a RAMS analysis; some data is even lacking at all, like the costs for inspection etc. For a full and comprehensive optimization that data is needed. Therefore the registration and collection of RAMS related data must be started right away and the necessity for this has to be communicated to all being involved. In a sense the same goes for LCC data, where a lot of data is hidden or obscured due to the fact its collection did not follow a standardized scheme.

Suggested actions: Step 1: Define what data is required and look for available data that can be (re-)used. Step 2: Start an infrastructure data collection project that uses clear definitions for necessary data for RAMS and LCC the optimal way this should be obtained.

Cost/time requirement: Step 1 Cost low, time low. Step 2: Cost medium, time medium

4.6.2 Optimal renewal point for track/components

The question of what the optimal renewal point would be for a full track or track components is directly related to the question on how good existing rules are. This may only be answered from consistent and permanent monitoring of the track condition. Reference track sections could be chosen to start a representative study for parametric dependencies of the track decay. The assumption is that it will depend on the specifics of a track design paired with the type, speed and load of the traffic, but also on local parameters such as the subgrade (soil), the risk of hazard related damage and on maintenance (tamping, rail grinding, wheel condition etc.).

Suggested actions: Initialize project, in which existing rules on component or whole track replacements are tested. This could be done with a “big data” analysis of track diagnostics data paired with renewal times of components or tracks.

Cost/time requirement: Cost medium, time medium

4.6.3 A function to describe the track performance

Another question that came up in the holistic optimization approach of Go-Leise was, whether a function could be formulated for the optimization. Such a function would have to yield a result that directly relates to the track performance (in terms of RAMS, LCC, noise and vibrations). The follow up question is then what needs to go into it. There are some obvious existing functions related to track performance that could be tested for the holistic Go-Leise approach.

Another possible approach would be a scaling function that relates track performance to the relevant parameters of the Go-Leise project (RAMS, LCC, noise and vibrations). The function could i.e. be cast into the following form:

$$TPI \sim (1+R)^{q} \cdot (1+A)^{t} \cdot (1+M)^{u} \cdot (1+S)^{w} \cdot (1+LCC)^{x} \cdot (1+N)^{y} \cdot (1+V)^{z}$$

TPI	**T**rack **P**erformance **I**ndicator
$0 < R < \infty$	**R**eliability as mean time between failures
$0 < A < \infty$	(un-) **A**vailability as delay time per million kilometers
$0 < M < \infty$	**M**aintainability as annual closure time due to maintenance
$0 < S < \infty$	**S**afety as mean time between safety system failures
$0 < LCC < \infty$	**L**ife **C**ycle **C**ost as sum over all direct and indirect costs per meter and hour related to investments, renewal, preservation etc.
$0 < N < \infty$	**N**oise in dB at 7.5 m from track above a *local* threshold level
$0 < V < \infty$	Ground **V**ibrations in dB at 8 m from track above a *local* threshold level
$0 < q/w$	As scaling exponents of positive effects
$0 > t/u/x/y/z$	As scaling exponents of negative effects

The scaling exponents introduce a weighting in the relation that would have to be determined empirically. Additionally a weighting and/or normalization could already be performed on the input parameters.

Alternatively a direct utilization of the rating values from the impact tables seems plausible. The weighting is then already been done in the MCDA factoring. Also more complex approaches may be taken such as probabilistic ones or others that aim at also incorporating some of the physical mechanisms involved in the decay of the track (which would likely mean a modeling of track dynamics and failures in conjunction with a virtual fleet for long time studies).

Suggested actions: Case 1: Determine if existing functions for track performance exist and whether they can be enhanced with missing elements as well as noise and vibrations. The aim could be a single number index. Case 2: Formulate a function as i.e. done above and find the relevant physical relations from existing data (literature research) and field tests. A weighting must additionally be applied to reflect (local) likings and requirements.

Cost/time requirement: Case 1: Cost low, time low. Case 2: Cost medium, time medium

4.6.4 Aging effects

It was found from the discussions and interviews in the Go-Leise project that aging is often disregarded or not accounted for. The discussion was mainly on rail pads as it was suspected that their dynamic stiffness could have changed over time, but aging of material of the track generally is an important parameter for all parts since it changes for example the probability for material failure, hence being a key component to RAMS and LCC.

Often the manufacturing companies will have performed stress tests on their products that will generally include tests for aging i.e. by applying the expected number of loading times for the next 10 or even 100 years in a laboratory setup over a much shorter period of time. The component’s characteristic features are measured before and after the tests and the differences are taken to be the result of aging. This however implies that the correct properties were measured, the setup was able to mimic the in track dynamics and all other types of degradation such as corrosion or evaporation of solvers. Additionally, when comparing products from different manufacturers which all had their own test methods, it is important that these methods will actually yield comparable results. Standardized test procedures will enhance the comparability while tests for aging would have to be validated from real track usage (i.e. by removing samples for laboratory testing at certain time steps).

Suggested actions: Step 1: Look for or develop an aging test that simulates real track usage under laboratory conditions either component wise or for larger parts of the track. Step 2: for validation purposes, start a project that compares aging from real track usage to the estimated effects of laboratory tests. The superficially aged products could also be used in tests for noise, vibration and asset management performance, either under laboratory or real life conditions.

Cost/time requirement: Step 1: Cost medium, time medium. Step 2: Cost high, time very high

4.7 Statistics and design of experiments

4.7.1 Guidelines for tests in the rail sector

There is usually a high variability in the results from tests with track components. There is no consensus on a guideline or set of standards to be used for testing components in the railway sector so that reliable results can be achieved in light of this variability. Such a guideline would include suggestions for design of experiments (including methods to determine the number of replicates) and statistical tests.

Before a general guideline can be written it must be agreed upon what parameters are the important ones, however they themselves must be determined from case studies including experimental field tests. A stepwise approach hence seems reasonable, where in a first step key parameters are identified which to our current understanding play a dominant role in the evaluation and optimization of the track. The performance of a track with a certain measure or in a certain state could then be evaluated with respect to these key parameters.
In-situ tests could have the following key parameters to be determined:

- Noise: A-weighted, equivalent sound pressure level at the ISO 3095 standard position (sideways in a distance 7.5 m from the center of the nearest track 1.2 m above the rail head). The sound pressure levels must be acquired as 1/3 octave band spectral information.
- Vibrations: equivalent velocity level at the reference position defined in the RIVAS project (sideways in a distance of 8 m from the center of the track on a ground spike). The velocity levels must be acquired as 1/3 octave band spectral information. If no soil properties are determined there should be additional measurement points at 16 m and 32 m respectively.
- TDR: according to EN 15461
- Rail roughness: according to EN 15610
- Soil: according to DIN 45672

For many of the components used in the rail sector guidelines exist and for some even standards exist that describe the way information is to be obtained about them. Variability however may still be found in the evaluation or comparison of data as it has multiple causes and not all of them must have been addressed in the guidelines or standards. The major reasons for uncertain results are given below

- Test method (sub-optimal method)
- Test procedure (misapplication or erroneous handling of an otherwise correct method)
- Equipment (sub optimal or non-standardized choice of measurement devices and tools for data collection)

- Local boundary conditions (interactions not considered as to ground, weather, track condition, buildings, flora etc.)
- Local variances (such as the roughness across and along the rail)
- Quality of test object (variance in the quality of products)
- Wrong or incomplete design of experiments (e.g. not enough repetitions)
- Badly formulated hypothesis.
- Statistics (averaging of incomparable sets of data or a wrong weighting, inappropriate statistical tests)
- Analysis (erroneous tools or choices in the post processing)
- Conclusions (wrong conclusions can be drawn due to lack of information/unknown parameters)
- Preconceived conclusions leading to discarding of unfitting data points.

No experiment or investigation will produce an absolute result for a given task within a finite time; therefore the aim of a guideline must as well be to minimize the uncertainties whilst keeping test procedures manageable and costs acceptable (i.e. include statistical uncertainty analysis of the final result)

Variances from the testing itself may be minimized by verifying if the method, procedure, equipment and analysis tools are the correct ones to use. The uncertainties to local boundary conditions can only be addressed by either reusing the same test environment or by a careful recording of boundary conditions and a later reassessment of their impact. Finally the variation obtained from the spread in quality of test objects, local variances and erroneous statistics is improved by

a. Averaging over repetitions for the same measurement point.
b. Repeating the test procedure on distinct yet related positions (i.e. measuring rail roughness on additional lines within the running band and/or some distance down the track)
c. For individual samples more than one sample should be tested

As many of the track components underwent stress testing from the manufacturer the procedures for product specification should be standardized or at least be made comparable. It must also be made certain, that the correct properties for the evaluation of the performance of a track component are being supplied (see also 4.6.4).

Suggested actions: Compile a comprehensive design of experiments guideline for the field of noise and vibrations that combines statistical modeling and design of experiments expertise combined with engineering and noise measurement experience.

Cost/time requirement: Cost low, time low

4.7.2 Test track design

Implementation of specific test track sections for comparability and known boundary conditions requires a definition of criteria, an analysis of possibilities (taking into account e.g. representativeness, easy access), possibly validation measurements on test sections and choice. It will also be necessary to make sure that no track renewal or other changes are foreseen during the time the test track is in use.

Suggested actions: Define criteria for test track sections. Analyze possibilities and make a choice of one or several possibilities.

Cost/time requirement: Cost medium, time medium

4.8 New/innovative ideas

4.8.1 Alternative track layouts

A non-discrete (or even random) pattern of the track layout could prevent the formation of clear pass- and stop bands for wave propagation in the rail and hence noise and the strong parametric excitation in a narrow frequency band for ground vibrations. This non-discrete pattern could for example be achieved with varying sleeper spacing or – if the spacing is kept the same – by randomly changing the geometry (e.g. width) of the rail pads from one sleeper to the next. Rail pad pattern could be cast with random stiffness modification along the track.

Suggested actions: Step 1: Simulate the effect of random supports and alternated stiffness in the track layout on noise and vibrations for all sorts of traffic. Step 2: Setup a test track with different stiffness configurations (rail pad) along the track and measure TDR and noise and vibrations from pass-byes. Compare to simulation results. Step 3: Setup test track sections with major changes to track layouts such as a random sleeper spacing or the usage of different sleepers and/or USP and rail pads. In addition the effect on asset management should be taken into account. Step 2 and 3 are suited to look into costs of the alternative track lay-outs. Step 3 would be suited to look into the effect on RAMS in more details as we expect this phase to run over a longer time period.

Cost/time requirement: Step 1: Cost low, time low. Step 2: Cost medium, time medium. Step 3: Cost very high, time very high

4.8.2 Friction modifiers

The idea of applying friction modifiers primary aims at reducing wear lowering the risk of rolling contact fatigue due to a higher degree of elastic deformations in the wheel/rail contact zone. It should also help to prevent roll-slip oscillations which relate to squealing noises and corrugation. Additionally it may impact the roughness formation. Particularly with higher axle loads and/or higher traffic the condition of the rail head gains in importance.

Suggested actions: Setup a test track section with and without friction modifiers and measure noise and vibrations as well as rail roughness periodically over a longer time period. This could possibly be combined with a trial on roughness growth by using a friction modifier on part of a section where roughness is measured periodically.

Cost/time requirement: Cost low, time high

4.9 Knowledge and data management

In the current Phase 1 of the project a document and data management system was developed for all relevant references collected for the Go Leise project. The system has also proposed and partially built up a database of references and data produced by the project. To that extent, both document management and measurement data formats were investigated and proposed. These will be helpful in the next phases of Go Leise, where field tests and experiments will be carried out. The resulting data will be stored in a standardized format and made available in the literature management system.

For the document management or content management system, an excel based system was selected, on the basis of the criteria analysis presented in the following table:

Table 1 Options for Content Management Systems evaluated along the criteria for Go-Leise

	Robust, reliable and safe	Purchase and installation	Maintenance cost	Ease of use	Flexibility to future expansions	Independence of OS	Overall score
Standard CMS	+/-	-	-	+/-	--	-	-5
Custom made CMS	+/-	--	--	+	+	-	-3
Open source CMS	-	+	+	+/-	-	+	+1
Office based tool	+	++	++	--	+	+	+5

For the storage of measurement data, a format was to be developed which would also be based on MS Excel. The measurement data format (intended for noise and vibration measurement data) is based on Excel as well and is described in detail in deliverable 3c.

5

Conclusions and outlook

Phase 1 of the Go-Leise project was concluded in October 2016. Its main results are presented in the current report. The objective of Phase 1 was an inventory, both of existing and emerging knowledge on the performance of the track with respect to noise, vibrations, reliability, availability, maintainability, safety and cost; and of methods and measures to improve that performance in a holistic way. This means that one or more aspects of the performance are to be improved, without causing an unacceptable impact on one of the other aspects. Suggestions for decision support and aiding methodologies were given to help make the necessary “holistic” decisions in this multi-dimensional, multi criteria issue, and taking into account that the real decision making process generally involves a multitude of decision makers.

The inventory covered relevant departments of the Swiss Federal Railways SBB, through the active participation of SBB experts. It also covered open literature and the knowledge available in the contractors for Phase 1, i.e. Müller-BBM, M+P and dBvision. In addition to that, renowned experts in most of the relevant fields were consulted in interviews and in a workshop organised by the project. As a result of this, Phase 1 was capable to deliver a comprehensive overview of measures and their effects, including the mechanisms behind these effects. In doing so, the project has contributed to a better understanding of the issues.

Nevertheless, significant gaps of knowledge were identified. To a certain extent these are lacunae in available data, simply because data were not collected in such as way that the required information can be drawn from that data. This applies particularly to accounted cost figures for maintenance cost of the different track elements. In addition to these lacunae, some effects that are observed are not sufficiently understood yet to make reliable predictions, let alone to predict the effect of certain interventions that have not been made before. This applies for instance to the generation and growth of rail roughness and corrugation. It is clear that this is an effect of wheel rail contact, but the phenomena involved and their effect on the rate of roughness growth and the regeneration of roughness after grinding is not sufficiently understood.

Phase 2 of the project was designed and intended to set up experiments in order to collect information that would help to bridge the knowledge gaps. Some of the effects to be studied are relatively slow and it therefore will take long before a significant result can be obtained. The corresponding experiments should be set up as soon as possible, without neglecting however the design phase of the experiment, in which the exact set up, the type and accuracy of the data to be collected, the required conditions, and the duration of the experiments should be carefully specified.

On the other hand, many quick wins could be found in simply collecting data that has not been collected in a systematic way before. Deciding about priorities, both in starting time and duration, as well as in being part of further investigations or not, is going to be an important and indispensable first step of Phase 2. The optimization methods evaluated in Task 2 of this first phase may be helpful in the process to decide about these priorities.

For the consecutive phases 3 and 4, it is difficult to foresee what the content will be. Once sufficient data and information comes in from Phase 2, optimization processes can be tested both for the entire network (phase 3) and for specific spots (phase 4). Probably some kind of feedback loop may be necessary in these phases, where for instance additional experiments may be required to support the decisions made in phase 3 and 4. Thus the Go-Leise project, once finalised, will enable the management of SBB to build upon a holistic view of the track system and to continue its continuous and consistent improvement.

6

Annex: List of knowledge gaps

In the following all knowledge gaps identified within the Go-Leise project but not addressed in chapter 5 are listed with respect to their affiliation. The gaps were classified to relate to track components or individual measures or to overall issues such as data collection and statistics. Also added were innovative ideas.

6.1 Impact and performance of track components

6.1.1 Rail grinding

1. Evaluate the usefulness of acoustic rail grinding so as to produce a comparison of roughness after acoustic grinding/finish to the average roughness after grinding with current SBB methods.
2. Examine the impact of grinding marks in the SBB network (what is the wavelength of the grinding marks, how much noise do they add and how fast are they wearing off-steel grade dependent); the result also is expected to depend on track usage
3. As acoustic grinding is likely to be part of the preventive grinding a cost split up for preventive and acoustic grinding combined is required in LCC.
4. Grinding benefits are dependent on specific track usage, therefore the noise benefits will fluctuate over the SBB rail network such that an optimization will need to take this into account.
5. It’s not always clear, if the measured rail roughness is the same as the roughness the wheels are in contact with. *(Solution: measure additional lines within the running band)*
6. Impact of grinding on the generation of head checks.

6.1.2 Rail dampers

1. There are suggestions that rail dampers can interfere with roughness formation. This would have to be evaluated before putting rail dampers into heavy use of excluding them at all
2. There are no published reports on long term costs and benefits from rail dampers and only little statistically usable data.
3. Some studies show a decrease of effectiveness in time. What are the reasons for this?

Note: Knowledge gaps concerning rail dampers have a low priority because after extensive trials SBB does not recommend their use.

6.1.3 Under sleeper pads (USP)

1. There is an ongoing debate on how rail roughness and rail irregularities develop on tracks with USP.
2. There is little guidance on how to adjust USP stiffness and damping to specific train traffic. Vehicle on track and track resonance may need to be tailored to local conditions.
3. What is the benefit of USP in straight lines and how big are the costs/efforts to compensate for noise increase (what can be done to compensate noise increase)?
4. Are LCC investigations from other countries i.e. Austria applicable to SBB?

6.1.4 Rail pad

1. There is an ongoing debate on whether the use of hard rail pads increases the roughness formation. This is related to the general knowledge gap about roughness growth rates.
2. There are findings that report a loss of dynamic stiffness in aged rail pads while other studies on rubber elements show a clear increase of (static) stiffness.
3. To improve ground vibrations and noise likewise it could be beneficial if the damping of the rail pad could be changed independently.
4. There are some suggestions that higher damping may cause faster wear of the rail pad.
5. As soft rail pads are often made from the same material as hard rail pads but with a reduced contact area the design can have an impact (air pockets, heat transfer, etc.).
6. Variety of different rail pad types available from manufacturers
7. What are the stiffness and damping ranges for rail pads (minimum/maximum values before damaging/running into safety issues)?

6.1.5 Rail

1. The impact of profile changes must be further investigated (the studies conducted were overall track optimizations). Noise and vibrations should be considered likewise.
2. The redesign limits for rails to be used in the SBB network may be narrow.
3. If using different rail profiles in a network there must be transition zones, the impact of which needs to be taken into account while judging costs and benefits.
4. Recent experiences in Germany and the Netherlands indicate that a better steel grade might introduce new, previously unknown problems such as the increase of the number of squats. This phenomenon needs to be understood as it might have an enormous influence on the track condition and thus on all aspects.
5. Impact of steel type and grade on roughness formation.

6.1.6 Rail fastening

1. There are reports showing a strong correlation of preload and TDR and thereby noise.

2. The fixation of the fastener on the sleeper can make for some of the fastenings resilience.
3. It could be beneficial to have more fixation points on a sleeper and hence along the rail.

6.1.7 Sleeper

1. The importance of the coupling of sleeper modes to rail vibrations above the rail resonance frequency is unclear.
2. Impact of the sleeper material (composite/wooden/concrete/etc.) on overall track performance must be further worked out.
3. With composite sleepers new sleeper shapes become possible.

6.1.8 Under ballast mats (UBM)

1. There is a discourse about the stability and settlement with the use of soft under ballast mats.

6.1.9 Ballast

1. The difference in ballast quality (impact on track behavior) should be looked at and indicators should be derived that describe the quality.

6.1.10 Soil

1. How can the relevant soil properties be measured?
2. What is the relevance of the soil to (low frequency) ground vibrations?
3. Impact of sub-ballast on LCC?
4. How to best improve the (sub-) soil?
1. Can heavy masses next to the track mitigate vibrations?

6.2 Interactions and overall optimization strategies

6.2.1 Collecting data and optimization

1. To our knowledge Go Leise represents the first time a holistic optimization for rail (RAMS/LCC/noise/vibrations) is applied. So, there is no other experience yet or any guideline how to approach this.
2. The comparability and quality of experimental/deduced data is questionable. Data that is gathered in other countries by experiments or cost figures may not be applicable to the Swiss situation.
3. Multi Criteria Design Analysis is a less well-known method and there is less experience with this method. It takes a learning time to get familiar with the methodology.
4. The sensitivity of the decision analysis method in slightly different, monetarization and/or weightings is not yet known.
5. What is the effort to test for LCC and how should this be done?

6. Are optimum materials being used in the individual track components?
7. At which length is a measure best applied if transition zones are required?
8. How important is wheel roughness of traffic? How could wheels be monitored?
9. How to best involve suppliers/manufacturers to disseminate/motivate optimizations and new developments?
10. How to optimize within political framework? (i.e. investment cost vs maintenance cost)?
11. How to best incorporate local preferences? (i.e. track improvements over noise barriers in touristic areas).

6.2.2 Statistics and design of experiments

1. Measurements show a large variability in noise from one boogie to the next in a train with the same type wagons. The influence of this on the evaluation of noise data must be studied.
2. Methods must be found to statistically compare different curves, e.g. frequency dependent relationships such as TDR values.
3. When changing multiple components in the track, interactions can or may happen we don't know off yet caused by unknown parameter dependencies. One example is the possible influence of rail dampers on the growth of the rail roughness.
4. The overall track performance may interplay with parameters overlooked or ruled out in the Go-Leise approach. As the scope of Go-Leise is already rather broad this should be even more an issue for investigations with a narrower focus.
5. When you go from one track type to another there is always a transition zones. At transition zones extra maintenance is needed. But what extra maintenance is needed, how much more often is it needed and how will that influence the optimization? Also some types of transitions may not be possible directly and may require intermediate zones.
6. Comparability: Strict recordings of similarities and differences of “same track” systems must be kept while comparing results from different locations/tests.
7. Statistics on track damage must be kept.
8. Lack of detailed LCC costs for entire tracks and components (historic data is often falsified by cross financing from different funds and subsidies).
9. Is monitoring performance of maintenance important?

6.3 New/innovative ideas

1. Added resilience in the ballast to prevent ballast crashing. For examplel it was suggested to add rubber granulates in the ballast.
2. Concrete walls next to the ballast could be used to lock up the ballast. This hinders the ballast to move which might cause less settlement of the ballast. This has the advantage of less maintenance/tamping and less vibration.
3. The current system is based upon a discrete adaption of components, so for instance change from hard to soft rail pads. A different approach would be to use a

continuous optimization to find the optimal track design. This requires an extensive mathematical model taking into account all relevant parameters, describing the behavior of the track. This approach can lead to new unexpected results. An example of such an application is a car tire design made by Michelin in the past. In this revolutionary design there was no air column in the tire as it turned out there was no function for it.

4. Could the rail damping effect of conventional rail dampers be somehow incorporated into other track components (i.e. fastener) to maintain a simpler track layout for lower maintenance efforts?
5. Integrated systems i.e. isolator (pad) integrated into the fastener. Sleepers with integrated supports?
6. Measures in the propagation path of ground vibrations such as suspended masses.

7

Colophon

Short Title
Go-Leise Final report

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