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Citation for the original published paper (version of record):

Ekberg, A., Paulsson, B., Elfgrén, L. (2018). Upgrading of freight railways to meet operational and market demands. Proceedings of 7th Transport Research Arena TRA 2018.
<http://dx.doi.org/10.5281/zenodo.1491480>

N.B. When citing this work, cite the original published paper.

Proceedings of 7th Transport Research Arena TRA 2018, April 16–19, 2018, Vienna, Austria

Upgrading of freight railways to meet operational and market demands

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Abstract

The European objective of a modal shift of freight transports to railways will require extensive upgrading of existing railway lines since very few dedicated freight railways are currently being built and existing lines were built for traffic demands at the time of construction. A transition to increased and enhanced railway freight operations can therefore be costly and complicated. To minimize negative effects, a guideline for upgrading was developed within the Capacity4Rail project. The current paper presents the major findings from this guideline. In particular it outlines different upgrading possibilities and their implications, and details structured approaches to upgrading analyses. Setting out from the Capacity4Rail handbook, the current paper discusses possibilities for upgrading of substructures, bridges, tunnels, and the track structure. In these areas, an overview of challenges and possibilities is presented together with examples of experience from operational upgrading. The paper concludes that freight line upgrading using a more streamlined approach as outlined in the guideline is a necessity if EU objectives on modal shifts in transportation are to be met. Further, it demonstrates why a political drive is necessary to increase efforts to upgrade freight lines.

Keywords: railway track technology; railway freight lines; structural integrity; asset management, bridges, tunnels

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Nomenclature

MGT Mega-Gross-Tonnes (million gross tonnes)

1. Introduction

Globally with a few exceptions, new railway lines are constructed for passenger traffic, often for high speeds or regional traffic. In contrast, an increased freight capacity is usually achieved through upgrading of existing lines. The consequence is that efficient methods and means to upgrade existing lines to meet new market and operational demands on freight traffic are increasingly important. In particular it is key to the fulfilment of the European objective of a modal shift of freight transports to railways within reasonable limits regarding economy, environment and time. To this end, the European research project Capacity4Rail recognized the need for a guideline to support upgrading. In particular, this guideline should promote a structured approach and highlight possibilities and challenges in different areas. The guideline should further incorporate knowledge from recent European and national research projects. The current paper condenses some main findings from this guideline, C4R D11.5 (2017).

2. Freight line upgrading – preliminaries

Operational experiences have indicated possibilities to upgrade railway lines in a very cost-efficient manner. As one example, upgrading of the line Ställdalen–Kil in Sweden in 1998–1999 was carried out at a cost of 250 MSEK. This should be compared with a cost of upgrading 15% of the line following regulations for new constructions, which was estimated at 1650 MSEK and required a longer construction time.

In particular it has been found that a systematic approach for upgrading that employs state-of-the-art knowledge will yield major benefits. However, despite the increasing needs for upgrading, and the enhanced knowledge on suitable methods, there has until now not existed any specific guideline founded on recent research and development. As mentioned above, one objective of the Capacity4Rail project was to address this shortcoming.

The first step in a structured approach to upgrade freight lines is to establish the objectives: What commercial and operational aims are to be fulfilled by the upgrading? Such objectives can be the ability to transport more goods in terms of volume and/or mass, faster freight transports, more reliable transports, cheaper transports etc. It is important to remember that different objectives *may* be contradictory and that the chosen objectives will result in technical restrictions and economic consequences. This may call for a need to prioritize objectives and also assign them a value. Ideally, such an assessment would answer questions such as: “What is an annual 5 MGT increase in freight volumes worth?” and “Will a risk of decreased reliability be acceptable if larger freight volumes are achieved?” Establishing the upgrading objectives is to a significant degree a political issue. The decisions will however have major operational, environmental, economic and technical consequences that may be hard to predict. Consequently, objectives need to be defined in a close and often iterative dialogue with experts in the fields.

Once objectives are established, there is a need to identify the most efficient means to achieve these. Here it should be emphasized that “upgrading” includes a wide variety of operational modifications such as longer trains, increased train weight, higher axle load and meter load, higher speed, increased loading gauge, more frequent operations and combinations of these measures. The efficiency of the different forms of upgrading on achieving the sought objectives will vary. Further, the different forms of upgrading will lead to very different demands on the infrastructure as will be discussed below. A summary of how different forms of upgrading affects different track structures is presented in Table 1.

To assess the consequences of different forms of upgrading, there is a need to understand and preferably quantify the consequences. This is a complex and cumbersome task that is addressed in the guideline through detailed investigation of how different parts of the track system are affected. In particular, the report goes into details on the consequences on substructure, bridges, tunnels, and track. Here the objectives are rather different: In simplistic terms, the main challenges for substructure and bridges is to ascertain the load carrying capacity and (if required) to improve it. For tunnel, the main complication is to ensure that there is sufficient space for the upgraded trains, and that there is sufficient time to carry out maintenance. For the track structure, the challenge is

to manage (and limit) the increase in deterioration that may follow from upgrading. These topics are elaborated in some detail in the following chapters.

Table 1 Impact of different upgrading scenarios on different types of structures

Structure / Upgrading scenario	Sub-structures	Bridges	Tunnels	Culverts	Retaining walls	Track	Switches & crossings
Longer trains	Some	Some	No	Some	No t	Some	Some
Increased train weight	Some	Some i	No	Some i	No i	Some	Some
Increased axle and meter loads	Great	Great	No	Great	Some	Great	Great
Higher speeds of freight trains	Some	Little	No	Little	Little	Some	Some
Increased loading gauges	No	No	Great	No	No	No	No

3. Preparing substructure for upgraded freight operations

3.1. Substructure assessment

Initially, root causes of substructure related problems in non-upgraded track, or with potential to occur under upgraded conditions need to be identified. These relates to high loads and/or a weak substructure. Here a major cause of high local load magnitudes is variations in track stiffness. Further, the propensity to high settlement rates (and potentially collapse) relates to poor/weak subgrade soils where also moisture levels (and related pore water pressure) have important effects on soil strength and stiffness. In particular, wetting and drying processes (including freezing and thawing cycles, as well as evapotranspiration) may contribute to soil deterioration and should be limited e.g. through proper drainage, which is described in a designated section of the guideline.

Input to an assessment of the substructure condition includes data from geophysical inspections, geotechnical investigations and track geometry measurements. Here, an extension of track geometry measurements to also include track stiffness measurements is useful to identify sections with large variations in track stiffness. These variations may cause distortions in track geometry that result in significant needs for maintenance, cf. Fig. 1. Track stiffness measurements can be done standstill or rolling. Examples of measured track stiffness variations in relation to where tamping works are presented in Fig. 1. In the guideline, also methods for geophysical inspection of substructure defects are described with details on benefits and drawbacks of the different methods. Further, possibilities for geotechnical investigations of substructure problems are described.

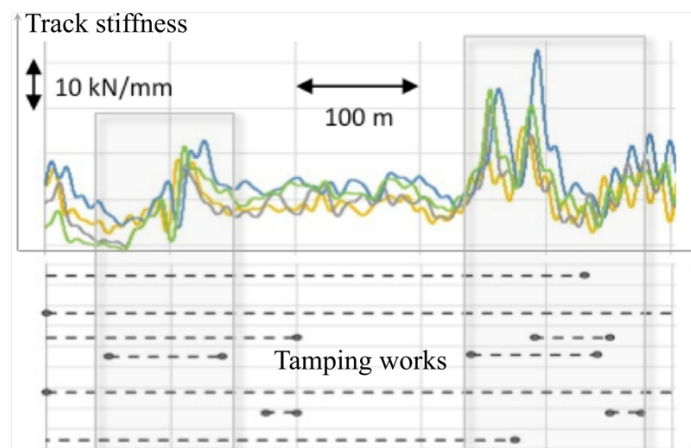


Fig. 1 – Registers of tamping operations associated to sudden stiffness variations. Adopted from Ribero (2014)

In addition to the identification of root causes for repeated track geometry problems, the substructure assessment should identify sections with poor bearing capacity and/or insufficient thickness of trackbed layers. The investigation methods discussed in the guideline all have advantages and drawbacks as detailed in the guideline.

For this reason, an intelligent combination of investigative methods is recommended. The specifics of such a combination need to be defined based on the local circumstances supported by the guideline. The final outcomes of the substructure assessment are suggestions on mitigating actions to be performed in the upgrading.

3.2. Subgrade improvements

Mitigation of a poor subgrade is often very costly. This includes not only the cost of material and work efforts, but also commonly extensive traffic disruptions that are caused by the mitigating actions. There is thus a significant cost saving potential in efficient reinforcement methods. However, innovative methods may be efficient only under certain conditions, or may not yet be sufficiently verified for large-scale implementation. For this reason, the guideline describes both benefits and drawbacks of available methods, and in particular for which conditions they are suited. This also includes which influence the reinforcement method has on existing traffic during installation. It should be noted that there are other improvement techniques than those described in the guideline. However, these are generally less suitable for existing embankments. However, as contractors continuously develop and/or adapt new methods to their machines, local geotechnical conditions, and railway related needs, this may change. The guideline should therefore be seen as an aid in identifying a suitable reinforcement method, and not as a restriction to innovation.

Methods described in the guideline include the deep mixing method, jet grouting, stabilizing berms with anchored walls, compaction grouting, precast concrete slab on piles, soil nailing, vibro-compaction, vibro-replacement, grouted stone columns, and vibro-concrete columns. Advantage and drawbacks of the methods are discussed and most of the methods are presented with illustrations.

As an example of the description, we consider the deep mixing method, which requires the following steps in design, execution and control:

1. Geotechnical survey and site investigations
2. Design of strengthening with lime cement columns
3. Quality control and safety plan for the installation
4. Analysis of possible restrictions on train speed and axle load during installation
5. Preparation of construction site
6. Transport of machinery, tools and materials for lime cement columns
7. Site supervision during construction
8. Follow-up after installation of strengthening

Examples of deep mixing carried out from the field side (inclined columns) and from the track (vertical columns) are presented in Fig. 2.

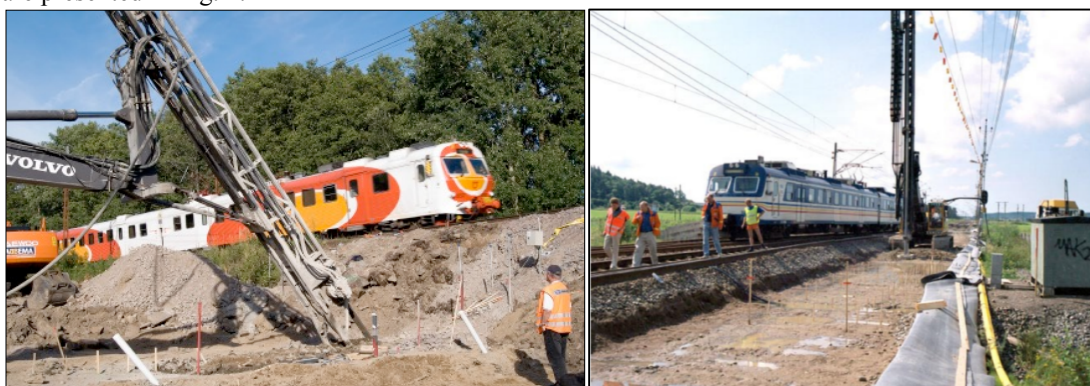


Fig. 2 – Deep mixing method. Example of installation of a lime column. Left: Inclined; Right: Vertical. From Innotrack (2008).

3.3. Example of subgrade improvements for upgraded freight operations

An estimation of costs and benefits of strengthening of the substructure is the upgrading of the Swedish Iron Ore line, see Paulsson (1998) where actions related to the subgrade referred to some 40% of a total upgrading cost on the order of 88 M€. The upgrade resulted in an increase in allowable axle load from 25 to 30 tonnes (20%), increased speed from 50 to 60 km/h (20%), and an extension of the train length from 470 to 740 metres (57%).

Investigations showed the upgrading to be very profitable from a socio-economic perspective although exact figures are impossible to calculate since the input data is not made public by the companies involved. It could be noted that the inability to demonstrate profitability of upgrading of freight lines due to lack of economy data is a general and important problem.

4. The influence of freight rail upgrading on bridges and tunnels

4.1. Assessment methods

The guideline sets out with an outline of differences in safety concepts between codes for new and existing structures. Many uncertainties that are present when building a new structure and that require a high safety factor, can be resolved when dealing with existing structures where actual loads, geometries and material properties (including deterioration rates) can be determined with a high accuracy. Probabilistic analyses are recommended when appropriate and values of the safety index β are discussed.

Assessment of existing structures as a preparation for upgrading is recommended to be carried out in three phases: Initial, Intermediate and Enhanced, see Fig. 3. The Initial phase may include a site visit, study of documentation and rough calculations. The Intermediate phase may include material investigations, detailed calculations and/or analyses, and further inspections and monitoring. The Enhanced phase usually consists of refined calculations and analyses that include statistical modelling and reliability based assessments, laboratory examinations and/or field-testing and economic decision analysis. A good assessment is often the most cost-effective way to upgrade a structure. Examples are given on how assessments indicating a high hidden capacity have been confirmed by full-scale tests to failure, cf. Sustainable Bridges (2008), Mainline (2014) and Paulsson et al (2016)

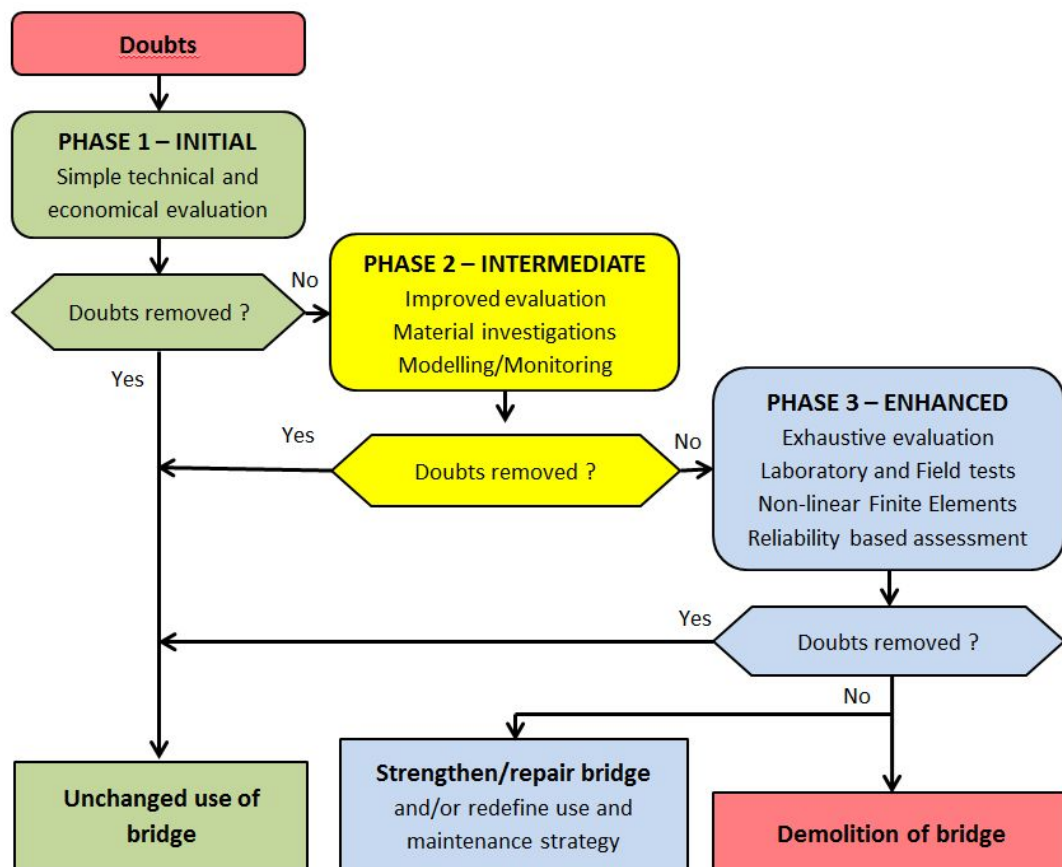


Fig. 3 – Flow chart for three-step assessment of bridge capacity. Sustainable Bridges (2008), Paulsson et al (2016)

4.2. Upgrading of bridges

For different kinds of bridges, specific areas for upgrading/repair are indicated in the guideline. Examples are also given on methods to use. These include refined calculations, increased cross sections of the bridge structure, change of system for static load distribution, external pre-stressing and the use of externally bonded fibre reinforced polymers (FRP). Examples of possible areas for reinforcement of concrete trough bridges, and available reinforcement methods to this end are given in Fig. 4 and Table 2, respectively.

4.3. Examples of reinforcement of bridges for upgraded freight operations

After an enhanced assessment process, and an evaluation of the applicability of potential reinforcement methods, it may be found that this is not a feasible approach. This is commonly the case for superstructures of old metal truss bridges where a partial replacement often is a cost-efficient approach to increase capacity and prolong service life of the whole structure. When replacing (part of) the superstructure or carrying out reinforcement work, there are commonly three critical constraints present: (1) working with short possession times; (2) limited substructure capacity; and (3) limited budget.

Overcoming these challenges require knowledge and abilities both in design and in production methods (where the guideline provides useful support), but can lead to significant savings. An example is the exchange of the steel truss deck of the arch bridge at Forsmo over the Ångerman River in Northern Sweden; see Fig. 4 and Collin et al. (2010). The upgrading carried a cost on the order of 65 MSEK to be compared with the estimated cost of 300 MSEK for a new bridge.

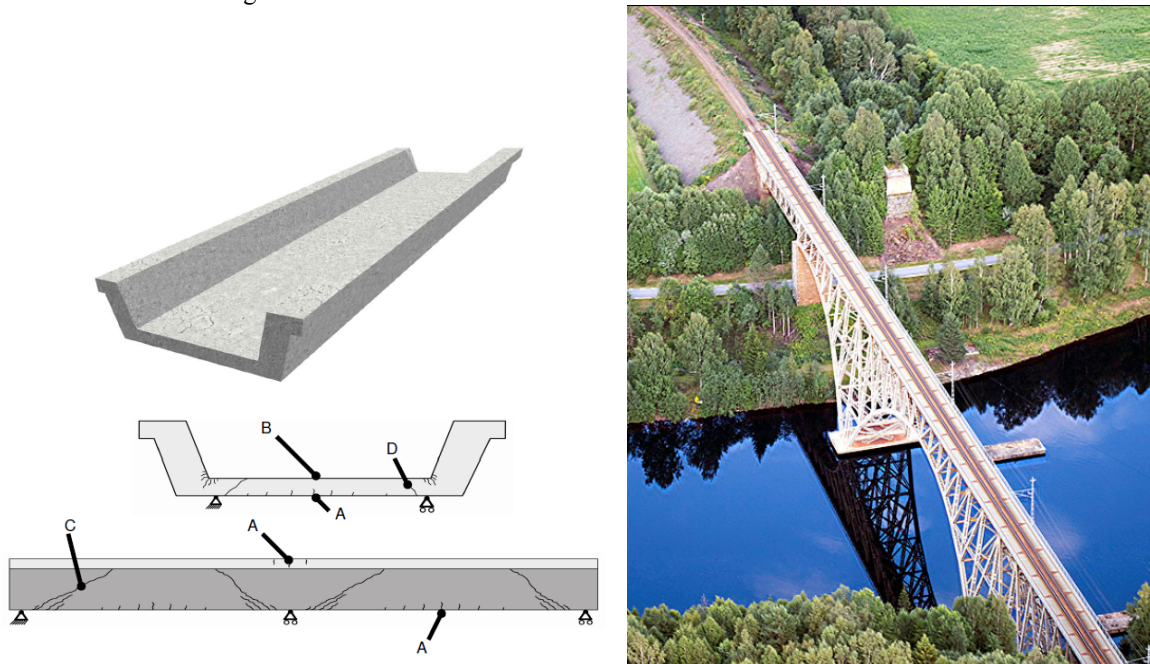


Fig. 4 – Left: Trough bridge with possible areas for reinforcement indicated. A – Deficient flexural bearing capacity; B – Deficient flexural capacity in areas hard to access; C – Deficient shear capacity in beams; D – Deficient shear capacity in slabs. Sustainable Bridges (2008).
Right: Forsmo bridge over Ångerman River, Sweden, after strengthening, Collin et al (2010)

Table 2 Examples of upgrading methods for concrete bridges, Sustainable Bridges (2007)

Deficiency	Upgrading method
A. Flexural bearing capacity	External Carbon Fibre Reinforced Polymer (CFRP) Plate or Sheet Mineral Based Composite (MBC) Near Surface Mounted Reinforcement (NSMR) External prestressing Increased cross section
B. Flexural bearing capacity hard to access	External prestressing Internal rods in drilled holes
C. Shear in beams	External Carbon Fibre Reinforced Polymer (CFRP) Plate or Sheet Mineral Based Composite (MBC) Near Surface Mounted Reinforcement (NSMR) External prestressing, longitudinal or transversal New stirrups and concrete casting Internal steel/CFRP rods Stitching Fibre reinforced shotcrete
D. Shear in slabs	Internal steel/CFRP rods Internal or external prestressing Increase of load-transfer area

4.4. Tunnel modifications in relation to upgraded freight operations

For tunnels, the guideline presents different cross-sections and typical loading gauges. Further, possibilities for maintenance and/or reinforcement work in tunnels with rail services in operation are discussed. Examples on conditions in countries like Germany, Austria, Switzerland, Sweden and the U.S. are presented.

5. Managing deterioration of track and switches & crossing under upgraded conditions

5.1. Assessing the influence of upgraded freight operations on deterioration of track and S&C

During efficient rail operations, it is inevitable that the track structure (included switches & crossings) will deteriorate over time. In general terms, the rate of deterioration accelerates with increase loading. Thus, a major consequence of upgraded freight conditions tends to be increased deterioration rates. Consequently, a main objective of a structured upgrading process is to ensure that deterioration rates are managed and kept at acceptable levels. To achieve this in an efficient manner requires predictive abilities to estimate the consequences of an upgrade, and translate this knowledge to efficient maintenance strategies.

The proposed methodology for predicting consequences of upgrading and defining a suitable upgrading strategy sets out from a two-stage assessment of deterioration as outlined in Fig. 5. The two stages are:

1. Assessment using experience based methods:

The intended upgrading on degradation, safety, costs etc. is assessed with rather simple models based on prior experience. These analyses provide an overview and a first estimation of the consequences (feasibility, costs etc.) of upgrading. A decision can then be made on whether a refined analyse is motivated in some parts based on uncertainties/risks regarding future degradation and/or safety levels. Experienced based methods can identify cost drivers in an overview manner, but they have limited capabilities in analysing the efficiency of different methods to improve safety, reduce costs etc. This is a consequence of that the methods are based on experience and empirical data and thereby in simplistic terms presume “operations as usual”.

2. Assessment using prediction based methods:

In this stage, consequences of upgrading are investigated in detail. To this end, numerical simulations (and where appropriate supporting tests) are employed. These investigations are more detailed and thereby require input data

on a much more detailed level than the experience based methods. Since the data relate to the characteristics of operating trains and the track structure, there is a need to define these before the analyses can take place. On the other hand, the input data are typically fairly well-defined and thereby usually easier to obtain than data for experienced based methods. Further, prediction based methods are ideal in investigating “what if”-scenarios where the effect of e.g. modifications in track characteristics on future deterioration can be assessed. Consequently, prediction based methods are not the best tool to estimate overall costs of upgrading, but ideal in investigating the effectiveness of different modifications and in supporting detailed cost analyses of sub-systems that have been identified as major cost drivers.

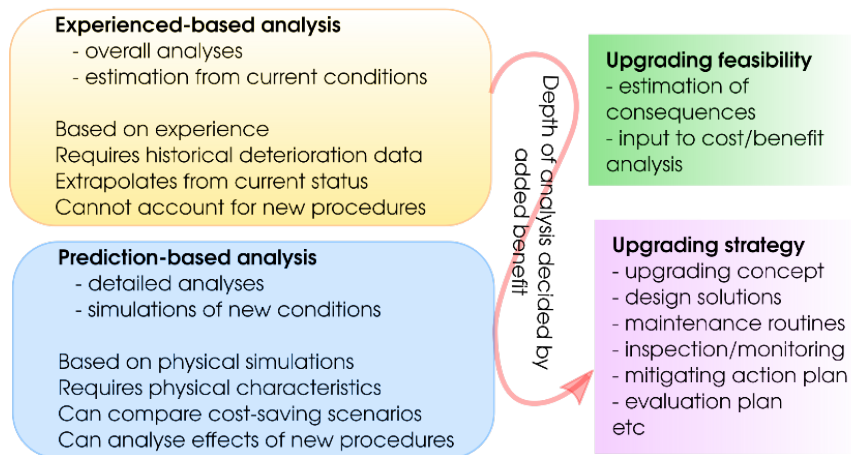


Fig. 5 – Outline of a two-stage assessment of consequences of upgrading on track deterioration

In the guideline, experienced-based and prediction-based methods of varying complexity are discussed in detail. In this context, the guideline notes that “degradation” implies a number of phenomena that differ in character, influential parameters and time to deterioration. This is illustrated in Table 3.

Table 3 Examples of track deterioration phenomena

Deterioration phenomenon	Main influencing parameters	Important material/ component features	Time to deterioration
Track settlement	Track forces (vertical and lateral)	Ballast (and sub-ballast) resistance	Medium
Sleeper damage	Vertical (impact) forces, support conditions	Reinforcement, sleeper design, sleeper support	Short if overloaded
Plastic flow	(Effective) stress magnitude	Yield limit, wheel/rail surface profiles	Short
Wear	Contact load (pressure and frictional), sliding distance	Hardness / yield limit	Medium
Plain fatigue	Stress amplitude	Fatigue limit, surface roughness, corrosion	Medium – long
Surface initiated rolling contact fatigue	Frictional contact stresses	Hardness, ductility	Medium – long
Subsurface initiated rolling contact fatigue	Contact pressure	Material defects, fatigue limit	Long

As noted above, different forms of upgrading will have different consequences. This is especially true for track degradation: An upgrade consisting of new vehicles often results in better running performance and reduced deterioration (or can allow for higher loading while keeping degradation levels constant). In contrast, an increased axle load will increase the (average) contact load, which will increase the propensity for wear, rolling contact fatigue, component fatigue, track settlements etc. A speed increase will lead to a larger scatter in contact load magnitudes, which may cause more damage (and in some cases a different type of damage) on wheels and rails. Operations at higher speeds are also more sensitive to (track geometry, rail/wheel profile and material) defects, which imposes stricter maintenance requirements. Increased capacity outtakes with existing fleet will

result in an increased loading per time unit, which will result in a faster degradation. At the same time, there is often less time for maintenance and repair and faults will become costlier since they will have a higher influence on operations (a given disruption will influence more goods).

The assessment scheme in Fig. 5 and the related methods that are discussed in the guideline can provide estimations on the consequences. The analyses can then be carried on until sufficiently detailed estimations of deterioration rates (and related consequences) are obtained. The ability to perform “what if” analyses allows for uncertainties to be identified and quantified. Note that “sufficiently detailed” is here commonly identified as the level at which more refined estimations will be too costly or require to extensive investigations. Note also that an upgrade analysis does not necessarily imply all steps in Fig. 5. As an example, a small upgrade, i.e. a slight increase in operating frequency on a line with moderate capacity utilization, would typically only require an empirical based analysis to provide a rough idea on increasing deterioration rates as a basis for future maintenance budgets. Finally, it should be noted that there is no clear-cut distinction between the different types of analyses: The more advanced experience based methods employ numerical simulations and prediction based methods typically employ empirical data for calibration and validation purposes. However, there is a major difference in that the experience based models put the emphasis on reflecting empirical trends, whereas the prediction based methods put the emphasis on reflecting the physical reality.

5.2. Examples of experience- and prediction-based methods to assess consequences of upgraded operations

The simplest estimation of increased degradation due to upgrading is to presume that deterioration rates, ΔQ , are proportional to the load, P (typically measured in MGT). This results in a linear relationship between load and track quality degradation on the form

$$\Delta Q = k \cdot P \quad (1)$$

where k is a constant. This approach is only suitable for small modifications in operational conditions. A more elaborate approach is to presume an exponential relationship between load and the (time dependent) track quality, as in Veit and Marschnig (2011)

$$Q(t) = Q_0 e^{bt} \quad (2)$$

where Q_0 is initial track b is a constant and t is time. The approach can be further extended by separating deterioration of different track components, see e.g. Öberg and Andersson (2009).

This is taken even further in the case of prediction based deterioration analyses where typically deterioration of a certain (or a few) deterioration mechanisms are considered in very high detail. An example is the use of numerical simulations of train–track interaction where the outcome can be employed e.g. to predict the risk of surface cracks on the rail using e.g. a shakedown-based fatigue index, FI_{surf} , see Ekberg et al (2013).

$$FI_{\text{surf}} = f - (2\pi abk) / (3F_z) \quad (3)$$

where f is the interfacial friction between wheel and rail, a and b are the semi-axes of the (presumably elliptic) contact patch, k is the cyclic yield limit of the rail material and F_z is the contact load between wheel and rail.

In the different areas covered in the guidelines, detailed descriptions including pros and cons of available models are presented. In general, prediction-based models include much more input parameters – equation (3) requires implicitly the entire set of parameters that define the dynamic properties of train and track – than experience-based. However, experienced based parameters are generally costlier to obtain and only valid to the operational conditions under which they were derived.

5.3. Management of upgraded track

The chapter on track degradation in the guideline concludes with a section on how to maintain the track under upgraded conditions. A number of maintenance actions are discussed. For all of these, a key factor in efficient maintenance is the ability to have a proactive maintenance planning. This relies on the ability to predict deterioration and thereby future maintenance needs. This has to be combined with efficient maintenance

methods, a topic that is getting more important as time in track is getting more scarce and costly. One possibility in this area that is discussed in the guideline is automation of maintenance.

5.4. Examples of the influence of upgraded freight operations on track degradation

When upgrading the Iron Ore line in Sweden, see LKAB, Jernbaneverket and Banverket (1997), the net increase in track related maintenance cost was predicted as 13.2 % with heavier axle loads. This also included effects of the expected increase in traffic. If grinding and lubrication was carried out the net increase in deterioration was predicted to be less than 2%. A follow-up after 10 years of operations showed that the increased deterioration was similar to the predicted increase.

6. Concluding remarks

Upgrading of existing lines for enhanced railway freight operations is essential if the European objective of a modal shift in transportations is to be a reality. However, there is currently no definite handbook for upgrading of railway freight lines. The paper presents and discusses some of the main results from a guideline developed in the Capacity4Rail-project that has been developed to address this need. It is based on latest research, which means that it is a viable alternative to current codes for new infrastructure, which commonly are based on knowledge which is at least 25 years old.

However, there are also other challenges in adopting upgrading strategies: Contractors have little interest in upgrading since contracting volumes are decreased to some 15–20% while risks increase. Consultancies have little interest in upgrading since it requires better knowledge/experience, i.e. more competence and less “volume work”. It is also an easy path for an infrastructure manager to build new instead of upgrading since current codes and tender processes are developed for new constructions. For this reason, there is a strong responsibility for the political sector to ensure that the economic, environmental and operational benefits of upgrading are exploited. To this end, we hope that the current paper provides the required knowledge on needs, challenges and possibilities in upgrading of freight lines.

Acknowledgements

The work is part of the activities within the National Centre of Excellence CHARMEC and Luleå Railway Center (JVTC). The research leading to these results has received funding from the European Community's Seventh Framework Programme [FP7/2007-2013] under Grant Agreement n°605650.

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