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Johannes Neuhold

Tamping within sustainable track asset management

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Tamping within sustainable track asset management

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Vorwort zur Schriftenreihe
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Das Institut für Eisenbahnwesen und Verkehrswirtschaft der Technischen Universität Graz beschäftigt sich als Institut der Fakultät für Bauingenieurwissenschaften mit der Eisenbahninfrastruktur, und zwar den bautechnischen Fragen des Errichtens des Fahrwegs, des Betrieb der Strecken und damit eng verknüpft seiner Wartung und Instandsetzung. Damit sind sämtliche für eine Betrachtung des gesamten Lebenszyklus der Infrastruktur erforderlichen Bausteine abgedeckt.

Das Einbeziehen wirtschaftlicher Bewertungen der Lebenszyklen erlaubt den Schwerpunkt „Nachhaltigkeit“ umfassend in technischer, betrieblicher und wirtschaftlicher Sicht abzudecken. Die Forschungsfragen betreffen dabei das Gleislageverhalten, mit der Zielsetzung dieses prognostizierbar zu machen und damit die Voraussetzung für präventive Instandhaltung zu schaffen. Die Forschung des Instituts in betrieblicher Hinsicht umfasst Fahrplangestaltung und eine auf Nachfrageprognosen aufbauende Netzentwicklung sowie Auswirkungen unterschiedlicher Verfügbarkeiten. Alle diese Themen werden im Forschungsbereich Life Cycle Management einer umfassenden wirtschaftlichen Bewertung zugeführt.

Mit diesem Ansatz versucht das Institut für Eisenbahnwesen und Verkehrswirtschaft seinem Anspruch, das System Eisenbahn in Forschung und Lehre zu vertreten, gerecht zu werden.

Tamping within sustainable track asset management

Mittels Prognosen aus den Zeitreihen vorhandener Zustandsdaten der Gleislageentwicklung kann die anzustrebende wirtschaftliche Nutzungsdauer des Eisenbahnoberbaus mittels Annuitätenmonitoring bestimmt werden. Der vorliegende 6. Band der Schriftenreihe zeigt auf, wie Menge und Zeitpunkt der häufigsten Instandhaltungsarbeit, dem Stopfen, spezifisch prognostiziert werden können. Das Besondere der vorgeschlagenen Stopfprognose ist, dass nicht nur das nächste Erreichen einer Eingriffsschwelle im Fokus steht, sondern dass langfristige Gleisverhalten und damit die Auswirkung auf die technische und damit auch wirtschaftliche Nutzungsdauer. Es handelt sich damit um einen Life Cycle Ansatz zur Bestimmung eines Stopfprogramms. Dazu wird aus den netzweit vorliegenden Verschlechterungsraten ein Prognosemodell entwickelt. Das Modell erlaubt einerseits allgemeine Stopfstrategien für die unterschiedlichsten Randbedingungen zu entwickeln, andererseits technisch-wirtschaftlich optimale Eingriffsschwellen zu identifizieren.

So kann beispielsweise gezeigt werden, dass konstante Eingriffsschwellen bei hohen Gleislagequalitäten nicht anzustreben sind, bei bereits niedrigem Qualitätsniveau zufolge eines hohen Alters des Oberbaus jedoch sehr wohl. Ein zusätzlicher Algorithmus *4tamp*^{ing} fasst die querschnittsbezogenen Prognosen zu umsetzbaren, wirtschaftlich sinnvollen Abschnittslängen zusammen. Beispielshafte Gegenüberstellungen von Stopfplanungen auf dieser neuen Basis mit aktuell umgesetzten Stopfungen zeigen hohe Einsparungspotentiale der Lebenszykluskosten, auch durch das Einführen von nicht konstanten Eingriffsschwellen. Die Wirksamkeit dieser Methodik kann damit nachgewiesen werden. Zudem können die grundsätzlichen Ansätze der Methodik in Zukunft auch zur Optimierung anderer Instandhaltungsmaßnahmen verwendet werden.

Peter Veit

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Abstract

Tamping is the most important maintenance task for ballasted tracks. Within a tamping action, the horizontal and vertical track geometry is restored and a stable and durable support for the sleepers is created. Besides track quality, tamping tasks can have significant influence on the reachable service life of tracks. Therefore, the planning process of tamping measures is of great importance. Over the last few years, the consideration of measuring data became an increasingly key part of the tamping scheduling process. However, a detailed prediction based on objective measuring data and especially the consequences of tamping tasks on the long-term track behaviour and the service life is still missing. Hence, in this thesis, a methodology is developed to plan tamping tasks automatically and thereby optimise life cycle costs.

The analyses show that the (modified) standard deviation of the longitudinal level is very well suited to describe track quality with regard to tamping scheduling. Furthermore, it is found that a linear deterioration model delivers the most reliable results for predicting the next tamping task. Additionally, a model is developed to determine the track quality behaviour after a tamping measure on the basis of many boundary conditions. This model allows for the specification of general tamping strategies as well as the calculation of an optimal intervention level in any specific situation. In a subsequent step, the algorithm *4tamp*^{ing} is generated that allows for the determination of reasonable section lengths for tamping. The basis for this is formed by the ideal point in time for an intervention in every single cross section. The application of *4tamp*^{ing} and the comparison with actually executed tasks show that it is possible to reduce life cycle costs by 20% due to the optimised tamping schedule.

In future, the methodology can be extended to other maintenance tasks and the renewal. Therefore, this thesis can form the basis for a comprehensive life cycle management tool, planning and coordinating different measures for the railway track in an optimised way.

Kurzfassung

Bei Stopfmaßnahmen handelt es sich um die wichtigsten Instandhaltungstätigkeiten für Gleise mit Schotteroberbau. Dabei wird die gewünschte horizontale und vertikale Gleislage wiederhergestellt und ein tragfähiges und möglichst dauerhaftes Auflager für die Schwellen geschaffen. Da sich Stopfmaßnahmen nicht nur auf die Gleislagequalität, sondern auch auf die erreichbare Nutzungsdauer auswirken, kommt deren Planung essentielle Bedeutung zu. In der Konzeption von Stopfprogrammen steigt die Bedeutung von Gleisgeometriemessdaten zwar, eine detaillierte Prognose aufgrund objektiver Messdaten wird jedoch selten vorgenommen. Zudem fehlt die Betrachtung der Auswirkung von Stopfeinsätzen auf das langfristige Gleislageverhalten sowie die Nutzungsdauer zumeist ganz. In der gegenständlichen Arbeit wird daher eine Methodik entwickelt, die eine automatisierte Stopfplanung aufgrund von Messdaten ermöglicht und dabei die Lebenszykluskosten der Gleisanlage optimiert.

Im Rahmen der Analysen hat sich herausgestellt, dass sich die modifizierte Standardabweichung der Längshöhe sehr gut eignet, um die Gleislage hinsichtlich einer Stopfplanung zu beschreiben. Es kann gezeigt werden, dass ein lineares Verschlechterungsmodell zur Prognose des nächsten Stopfeinsatzes die zuverlässigsten Ergebnisse liefert. Zudem wird ein Modell entwickelt, das es erlaubt, die Gleislageparameter nach einer Maßnahme aufgrund zahlreicher Einflussparameter zu bestimmen. Dieses Modell eröffnet in weiterer Folge die Möglichkeit allgemeine Stopfstrategien festzulegen, sowie die optimale Eingriffsschwelle für jede spezifische Situation zu berechnen. Im Rahmen der Arbeit wird weiters der Algorithmus *4tamp*^{ing} entwickelt, der aufgrund des optimalen Eingriffszeitpunktes in jedem Querschnitt automatisch sinnvolle Instandhaltungslängen erarbeitet. Die Anwendung von *4tamp*^{ing} auf Testabschnitten und der Vergleich mit tatsächlich ausgeführten Einsätzen zeigt, dass durch die optimierte Stopfplanung eine Reduktion der Lebenszykluskosten von 20% erreicht werden kann.

Die entwickelte Methodik kann in Zukunft auf weitere Instandhaltungstätigkeiten sowie die Gleiserneuerung ausgeweitet werden. Somit kann die vorliegende Arbeit als Basis für ein umfassendes Life Cycle Management Tool fungieren, das verschiedenste Tätigkeiten am Eisenbahnfahrweg optimal plant und untereinander koordiniert.

Contents

1

Introduction

With our world as interconnected as we find it today, transport systems are one of the most important backbones of our society. Previously, the transport of people and goods was carried out by horse-drawn vehicles and ships. With the development of the railway industry in the 19th century, a revolution of the transport sector was triggered and industrialisation was strongly advanced. The railway made it possible to overcome distances in quite a short time compared to all other transport modes at this time. Though, with the advent of road traffic after World War II, railways were severely disregarded and many lines were closed down. However, the demand for transport services has been ever increasing in recent decades and therefore the capacities in road and air traffic have been and are becoming increasingly scarce. Furthermore, railways exhibit some unique advantages compared to other transport modes: railways are very safe, environmentally friendly and allow for the transportation of a comparably high volume of passengers and goods. Also, railway operation at very high speeds is possible today. Due to the described facts, railways have experienced a significant upturn in the last few years and rapidly increasing traffic volumes can be observed which can also be assumed for the future.

To handle the increasing demands for train traffic, an appropriate infrastructure is an indispensable prerequisite. After the construction of the infrastructure, the different assets must be maintained during the service life. Maintenance tasks have to be executed to guarantee a functional condition and to remove failures. The standard EN 13306 [1] defines two main maintenance strategies: (i) preventive maintenance and (ii) reactive maintenance.

Besides the prevention of system failures, the optimisation of service life, improving safety, increasing availability, optimisation of operating procedures, reducing malfunctions or long-term planning of financial resources can be the goals of a maintenance regime. These general definitions are also true for a railway track.

In Austria and worldwide, the ballasted track is by far the most common type of track construction. The ballast bed contains a ballast layer that provides the support for the track grid (rails and sleepers) and distributes the loads into the subsoil. Due to train traffic and other impacts, rearrangements of the ballast grains, breakage and abrasion of the ballast stones occur [2]. These phenomena and also imperfections in the subsoil lead to settlements in the ballast bed and therefore in the whole track construction. These settlements mean a deviation from the original track position. Especially in the case of uneven settlements, this results in track geometry failures. These failures have negative effects on the riding quality of a train and in the worst case also on safety.

To avoid the negative consequences of track geometry failures, the track position is restored by means of tamping tasks.

A tamping measure corrects the vertical and horizontal position of the track and creates a stable and durable support for the sleepers. Besides the positive effects of such a task, it must be mentioned that tamping also contributes to ballast degradation [3] and therefore cannot be executed any number of times. Besides this, a maintenance action like tamping requires personnel, financial and technical resources. Furthermore, it is necessary to close the track temporarily, as it is not possible to execute the task and perform train operation at the same time.

Due to the above-mentioned facts, it is essential to plan tamping tasks in the best possible way, considering technical and economical boundary conditions. Over the last few years, taking measuring data into account has become an increasingly important part of tamping scheduling. However, a detailed prediction based on objective measuring data and especially the consequences of tamping tasks on the long-term track behaviour and the service life is still missing. The goal of this thesis is to develop a methodology for scheduling tamping tasks automatically, thereby optimising the life cycle costs of the asset. At the same time, this fact implies that considerations regarding safety are out of scope, as safety critical conditions require immediate interventions and do not provide any space for optimisation.

The Institute of Railway Engineering and Transport Economy of Graz University of Technology has been collaborating closely with the Austrian Federal Railways (ÖBB) for decades. Therefore, the analyses in the present thesis are executed with data form the Austrian railway network and assumptions are made based on the boundary conditions in Austria. Nevertheless, the developed algorithm can be adapted and applied for any railway network by adjusting the necessary parameters to the specifics of the related country.

In the first chapters of the thesis, the principles of a track construction are introduced and the different possibilities for maintaining a ballasted track are described. Furthermore, an extensive literature review is done to discuss the different existing practical and academic approaches for tamping scheduling. In a subsequent step, the algorithm *4tamp*^{ing} is developed to plan tamping tasks automatically in an optimised way for life cycle costs. To reach this goal, the following questions should be answered:

- Which parameter is best suited for describing track quality in terms of planning tamping tasks?
- Which deterioration model should be used to describe track quality over time and to predict the point in time when an intervention level is reached?
- Which parameters affect the track quality behaviour after a tamping task?
- Is it possible to set up a model for estimating the track quality behaviour after a tamping task based on different boundary conditions?
- Is it possible to formulate overall tamping strategies for different track types?
- What is the definition of an optimal intervention level and how is it possible to find the optimal intervention level?
- What are the effects of different intervention levels on life cycle costs?
- Which factors have to be considered to combine results of single cross sections to reasonable section lengths for tamping?
- Is it possible to develop an algorithm that enables for planning tamping tasks automatically and optimises life cycle costs?
- What are the interconnections between tamping tasks and other maintenance and renewal measures?

2

Track construction

The railway track is quite a complex engineering construction that has to fulfil the following main tasks [4]:

- Guide vehicles and guarantee safe railway operation.
- Absorb vertical and horizontal forces from train traffic and the environment.
- Distribute these forces via the track grid into underlying layers.
- Ensure high passenger comfort.
- Offer high availability for train traffic.

It has to be mentioned that the railway track is not a random combination of different parts; it is much more a composition of optimally coordinated components. This means each of these components fulfils its own, specific task and has to contribute to an optimal overall construction.

As trains exhibit high loads of up to 22.5 tons per axle (or even higher values on heavy haul lines in other countries), these forces cannot be handled by one single point or component. Rather it is necessary to distribute the loads step by step from the rail to the subsoil via a widening surface. To guarantee this load distribution, every component along the force path exhibits elastic behaviour to a specific degree. At the contact area between wheel and rail, a force of approximately 300,000 N/cm^2 is applied on a surface of about 3 cm^2 (Hertz area). As the rails exhibit the property of bending in a vertical direction, the forces are spread over a longer segment of about five to nine sleepers.

The next layer is the ballast bed, which distributes the loads on an area of about 10,000 cm^2 on the subsoil and reduces the force to around 6 N/cm^2 there. Figure 1 schematically shows the load and pressure distribution of one rail axle [4] [5] [6].

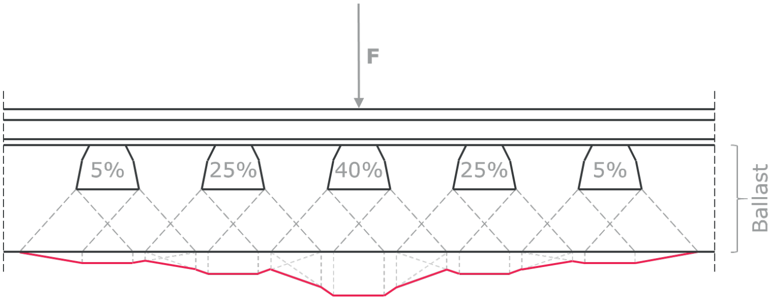


Figure 1: Load distribution resulting from one axle [7], according to [4].

As the number of trains and also the train loads are steadily raising, the requirements for the railway track are increasing as well. To meet these demands, the different components of the track construction were refined over the years and innovative products are applied.

For standard gauge, all over the world two main types of superstructure are established. Ballasted track has been used for centuries and constitutes the main superstructure type in Austria. As an answer to ever increasing demands (in particular high-speed traffic), different slab track systems were developed, and more and more new lines are equipped with this type of superstructure at an international level.

In Austria, the vast majority of tracks are built in the form of ballasted track. Slab tracks primarily constitute solutions for special sections – especially in tunnels. As tamping tasks can only be executed for ballasted tracks, it is the only system relevant to this thesis. Nevertheless, both systems are described briefly to point out their underlying advantages and disadvantages.

2.1 Ballasted track

Ballasted track is also called “classical track” or “conventional track” and has been used since the first big railway boom at the beginning of the 19th century. It is still the most extensively used system in the world and by far the most widely used superstructure type in Austria.

The structure of a classical ballasted track cross section is shown in Figure 2. A conventional ballasted track consists of a framework made up of rails and sleepers (track grid) which is supported on the ballast. The rails and sleepers are connected by means of fastenings and rail pads between the rails and the sleepers provide elasticity [5].

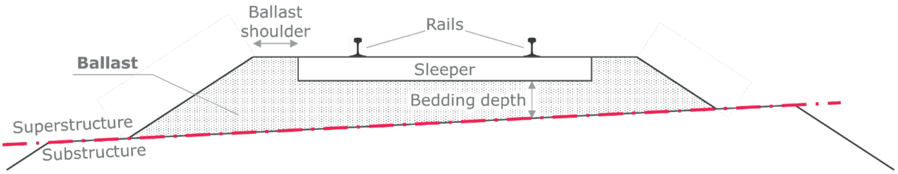


Figure 2: Cross section of ballasted track [7].

The principle of the ballasted track structure has not changed substantially since the beginning of the railways. However, some essential improvements like continuous welded rails, concrete sleepers with under sleeper pads, heavier rail profiles, innovative elastic fastenings, transition constructions or rail pads were made over the last decades. These innovations make ballasted track a contemporary superstructure that still satisfies the high demands, as demonstrated by high-speed traffic in Japan or France for example [5].

Subsequently, the most important components of the ballasted track are described briefly together with their most important types of wear that lead to disturbances within the system.

2.1.1 Rail

The rail is a very important component within the track construction, as it represents the direct contact area between vehicle and superstructure. It is a running surface, carrier and guiding element all in one. Therefore, the rail must provide high resistance to wear, compression, fatigue and brittle fracture, high yield strength, tensile strength, hardness and good weldability. Furthermore, a high degree of purity, a good surface quality, evenness of profile and low residual stress after manufacturing are expected.

Today, rails with the profile 60E1 are applied as standard. Usually rails are delivered with a “natural” hardness. These perlitic rails are named according to their crystallisation condition. When applying rails in small radii, they are thermally treated to increase their tensile strength and wear resistance.

As the rail is exposed to very high stresses, several types of wear like roll contact fatigue (e.g. “Head-Checks”, squats), side and height wear, skid marks, corrugation, indentations and wheel burns can occur [4].

2.1.2 Sleepers and fastening systems

Sleepers are designed to receive the loads from the rail and to distribute them to the ballast bed. Furthermore, they must hold the rails in height, to the sides and in longitudinal direction and maintain and establish track gauge. Besides the monobloc sleeper, which is the standard sleeper form, some special types like twin-block or frame sleepers are used in some cases. In the beginning of railway technology, timber was the preferred material for sleeper production. Over time, wooden sleepers were replaced by concrete sleepers and in some areas steel sleepers were utilised or are still in use [4]. In Austria, nowadays, concrete sleepers with under-sleeper pads are installed as state-of-the-art solutions as part of track renewals on medium to highly loaded lines [8]. These under-sleeper-pads increase the contact area between the sleepers and the ballast bed and provide elasticity in an otherwise quite stiff system [9] [10]. Therefore, under-sleeper-pads make it possible to stretch maintenance intervals and prolong the life span significantly, which leads to economic benefits over the service life [11].

The fastening system is the connection between the rail and the sleeper. Its tasks include retaining track gauge, resisting longitudinal movement of the rail, containing vertical movement of the rail and preventing rail roll-over. The rail pad is situated directly between the rail and the sleeper and has to resist rail creep and provide elasticity for the superstructure system [12].

The most widespread signs of wear for the components described above are broken or loose fastenings, broken or cracked sleepers (in case of wooden sleepers), and worn rail pads.

2.1.3 Ballast

The ballast bed represents a very important and sensitive component both from a technical and an economic point of view. The most important tasks the ballast bed has to perform are the following [4] [13]:

- Absorbing vertical, horizontal, longitudinal and buckling forces from the sleepers and distributing the loads into the substructure.
- Providing high resistance against longitudinal and horizontal displacements of sleepers.
- Enabling maintenance actions and easy recoverability of track geometry.
- Supplying enough elasticity for the superstructure to reduce dynamic forces.
- Guaranteeing permeability of water and air.

The overall quality of the ballast layer depends on the ballast thickness and width, the quality of the ballast grains and the quality of ballast compaction. When it comes to meeting the high requirements of railway ballast, not every material is suitable [14]. Therefore, hard stones like basalt, granite or quartzite are favoured because of their high wear-resistance. Furthermore, the grain size distribution of the material is of great importance to provide the required properties. In Austria, ballast for railway tracks exhibits a grain size of 31.5/63 mm [15] which is orientated to the specifications for track ballast regarding EN 13450 [16]. Detailed information regarding ballast quality is determined within the respective technical terms of delivery [17].

Over time, the ballast bed wears, and its properties are influenced negatively. This wear is mainly caused by the loads from train traffic. At the beginning of the service life, the wear types grain breakage and re-arrangement are dominant, which leads to quite high initial settlements. From a cumulated load of about 100,000 gt, spalling and especially abrasion are the prevalent types of wear [2].

Furthermore, maintenance tasks (abrasion caused by tamping), migration of fine particles from underlying layers, pollution due to loss of loads from freight trains and exogenous contamination lead to a fouled ballast bed. As a consequence, a fouled ballast bed loses its ability to perform its key functions and track geometry issues may arise [18].

2.1.4 Track formation, subsoil and dewatering

The track formation layer is the connecting component between superstructure and consisting soil. Its main function is to provide a stable support for the superstructure. An installation with uniform properties is essential to avoiding uneven track settlements and as a result track geometry problems. A track formation layer is mandatory if the subsoil’s bearing capacity is insufficient, ballast cannot be provided in the desired quality or subsoil has to be protected from frost [19].

Regarding the grain size of soils, coarse-grained, fine-grained and organic soils can be distinguished. Depending on the quality of existing soil and its bearing capacity, different measures may be necessary to improve its usability. In case of insufficient bearing capacities of the subsoil, grains re-arranging due to train traffic and plastic deformations can occur leading to track geometry issues [4].

Another essential component within the track construction is a well-functioning dewatering system. The system has to collect both surface and underground water and drain it appropriately. An inadequate drainage system can lead to a change in load distribution in a negative way. Furthermore, fine particles can move into the ballast layer, and there is a risk of uplifts as a result of frost [18].

2.2 Slab track

As described in chapter 2.1, the track's ballast bed is exposed to a wide range of wear mechanisms. Furthermore, traffic loads as well as operation speeds are steadily increasing, thus constituting additional burdens for the ballast bed. Within the development of slab track constructions, the idea was to substitute the ballast as the "weakest" component of the track construction with other materials like asphalt or concrete. As asphalt or concrete exhibit quite low plastic deformations, the required elasticity has to be introduced by means of separate elastic elements underneath the rail and the sleeper [4].

In contrast to the conventional superstructure with a ballast layer, slab track requires an almost settling-free substructure. Hence, slab track is often used on bridges and in tunnels. The biggest disadvantage of slab track is that retrospective adjustments and corrections are quite difficult and can only be executed under high outlay [20].

This means, if slab track should be applied on conventional earth substructures, the soil has to be improved in many cases to meet the high requirements. In transition zones, where ballasted track and slab track abut each other, special constructions have to be installed to reduce sudden changes in track stiffness [21].

Over time, different systems of slab track were developed. Figure 3 gives an overview of different construction types of slab track.

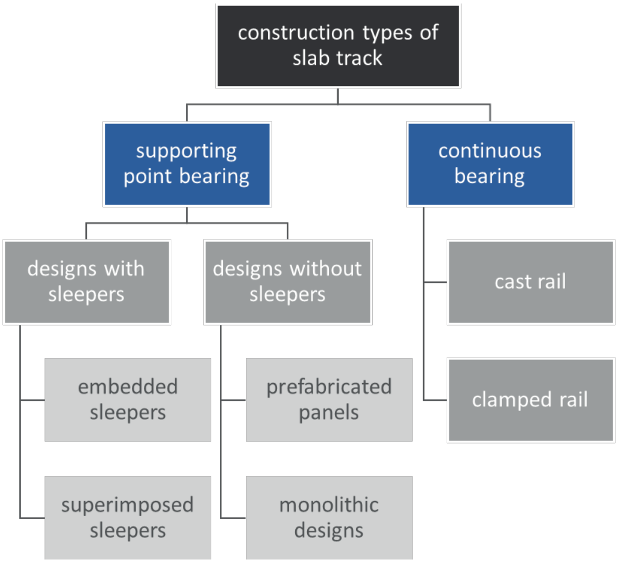


Figure 3: Different construction types of slab track, according to [22].

The system used in Austria is called Slab Track Austria (STA) or system ÖBB-PORR and was jointly developed by the Austrian Federal Railways and Allgemeine Baugesellschaft – A. Porr AG. The principle element of the system is the elastically supported slab with integrated rail support seats. The bottom of the slab, as well as the tapered openings, are attached with an elastomeric layer. The slabs are supported and fixed on a thin base layer of self-compacting concrete [23]. The special thing about this system is that the slabs can be replaced very easily if damaged. Furthermore, the system allows for relatively simple track adjustments in the event of differential track settlements. These properties make STA more flexible as opposed to other systems [24].

Compared to ballasted track, slab track systems need less maintenance, reach higher service lives and meet higher requirements regarding track geometry – provided the whole construction is properly executed. Despite their advantages, slab tracks have some inherent drawbacks: Installation of slab track is quite expensive and requires higher initial investments when compared to ballasted tracks.

Furthermore, it is not possible to execute track works (track laying, maintaining, renewing) with continuous working machinery. Additionally, corrections in track geometry are only possible up to a certain degree.

If a specific limit is reached, adjustments are only feasible through complex measures like ground injections. Because of these non-negligible disadvantages, the utilisation of slab tracks is limited to special fields of application like high-speed lines, bridges and tunnels [4] [13] [22] [25] [26].

Concerning maintenance, it can be summarised that the biggest advantage of slab track is also the biggest drawback: It is not necessary to tamp slab track, as it should exhibit a durable, sufficient track geometry during the service life, but it is also not possible to tamp slab track should corrections be required. Thus, this type of superstructure is not within the scope of the rest of this thesis, and only ballasted track is considered.

3

Maintenance for ballasted track

As described in chapter 2, ballasted track constructions consist of different components that are subject to many types of wear. To guarantee safe, comfortable, reliable and economically reasonable railway operation, it is necessary to maintain the components and to remove any occurring failures. One of the most sensible parts of the track construction is the ballast layer, which is the bedding for the track grid and therefore primarily responsible for adequate track geometry. When track geometry does not meet the requirements anymore, tamping tasks have to be executed to restore the desired track position. In case of relatively poor ballast condition, it might be that tamping actions do not exhibit the desired effects anymore or a restored track geometry degrades very fast after the action. In these cases, more complex measures like ballast cleaning have to be executed. Subsoil rehabilitation also involves manipulations of the ballast bed. This measure is however mostly executed alongside track renewal and not in the form of maintenance. This chapter should give a brief overview of the most important activities on the ballast bed. As this thesis mainly deals with the planning of tamping actions, the focus is on these tasks.

3.1 Tamping

Tamping tasks are the main maintenance actions performed in networks with ballasted tracks and therefore also the most important ones in terms of costs or maintenance budgets. Within the Austrian core network, tamping is executed every two to six years on average [27]. In the course of the works, the track grid is lifted, exactly positioned in a vertical and horizontal direction and the ballast underneath the sleepers is compacted through the tamping tines.

The tamping process fulfils the following main tasks [28]:

- Removal of vertical and horizontal track geometry failures to guarantee safety and railway operation with sufficient comfort.
- Removal of “hanging sleepers” and the generation of a homogenous, compacted and viable support for the track grid for an improved load distribution on several sleepers.
- Generation of a durable position stability to avoid a potential quick deterioration of track quality and the condition of track components.

By considering tamping tasks, two main types of tamping can be distinguished:

- Line tamping is the standard maintenance process for restoring track geometry over longer sections that deteriorate quite homogenously.
  The goal of this measure within a sustainable maintenance regime is to keep the ballasted track at a constant quality level.
- Spot tamping is used as an additional, necessary corrective maintenance task in an overall sustainable maintenance regime. As the name implies, spot tamping is limited to the correction of single failures. Single failures are track geometry issues that occur within a wavelength range of mostly 5 to 10 m and degrade comparably fast, while the surrounding sections exhibit quite good quality behaviour [29].

If the entire maintenance regime is set to a minimum level, line tamping would rapidly decrease, while spot tamping increases in terms of the number of spots and budget needed. This maintenance regime delivers lower costs in the short run in shifting the actual needs in the future. However, much more expensive maintenance actions or even renewals are the consequences from a long-term perspective, if traffic is to be run at the same quality (axle load, speed) and safety [30]. As the goal of the present thesis is to establish an optimised and sustainable maintenance schedule, the further investigations and analyses focus on line tamping only. This should cover the standard case within a well-maintained network.

Besides the open track, turnouts and crossings also require maintenance tasks in the form of tamping. These measures can be regarded as something like a specific type of single failure tamping and are also not within the scope of the present thesis. Nevertheless, both kinds of tamping are described briefly to show their working principles.

3.1.1 Line tamping

Before the tamping task itself can be executed, some preliminary works have to be done. These preparations consist mainly of two parts: The first one is site preparation of the infrastructure and includes tasks like drainage control, removal of wet spots, exchange of damaged sleepers, fastenings or rail pads, maintenance of rail joints, removal of any hindrances for the tamping process and the determination and supply of the right amount of fresh ballast. The second one is the specification of track geometry that should be established during the tamping process. There are two methods for maintaining track geometry [31]:

- Relative tamping uses the tamping machine's own reference system to balance the track to the height of the surrounding track level. These systems derive a design position for the track from its existing position. This means no reference to any external fixed point is ever made. If the track failure is expanding over a long area, there is a potential hazard that the endpoint of the measurement system may not have the right level, and the failure may transmit with the tamping process. For this reason, this correction is mainly used for short failures.
- Absolute tamping uses fixed reference points (measurement points at the railway track side) to determine the correction values to return the track to its absolute track geometry position. This type of correction needs a certain length of ramping at the beginning and the end of the tamped section and is primarily used for line tamping.

As the current focus is on line tamping, absolute tamping is the method relevant to the present thesis. Absolute tamping always involves a correction of a geometry deviation to a fixed level. This implies that this deviation has to be determined and the corresponding values for correcting the track geometry have to be calculated. This process is called pre-measurement and has to be performed in most cases within a separate temporary track closure before the tamping measure is executed. The most common methods for pre-measuring are hand-done geodetic measurements or automatic measurements by a special track pre-measuring car like EM-SAT [32]. The two possibilities are shown in Figure 4.

The latter system uses the principle of long chord measurement for determining defects in a vertical and horizontal direction. Afterwards, the exact control values for the tamping machine are calculated automatically. The machine is self-propelled and utilises a separate on-track laser satellite to increase the measuring base.

Figure 4: Geodetic pre-measurement (left) and EM-SAT (right [33]).

Besides the standard measuring principles, combined level and alignment laser measuring systems for vertical and horizontal track geometry and curve-lasers can be used, though only in combination with a tamping machine. Hand-guided measuring devices are another option for pre-measurement. A particularly noteworthy measurement method is the PALAS system that is mainly used in Switzerland. This laser measuring device is mounted on the front side of a tamping machine and orientates itself on a geodetic marking system (fixed points on catenary poles). As this system provides the correction values within the tamping process, it would theoretically be possible to omit a separate pre-measurement process.

Because of the lack of planning security (e.g. amount of fresh ballast), pre-measuring is nevertheless carried out separately [34]. To counteract the disadvantages of separate temporary track closures for common measuring methods, a system is developed that makes it possible to measure absolute track geometry under speeds up to 100 km/h in regular train operation. Therefore, stereo cameras on the train capture new graphical reference points (QR-codes) that are mounted on catenary poles for example. Subsequently, the absolute track quality can be calculated automatically [35].

The track geometry restoration process itself was carried out by means of pickaxes at the beginning of railways. Over time, these mechanical devices have been redeemed through electrical hand-held tamping units [36]. Rising speeds and traffic density soon required more sophisticated tools. This growing demand led to the development of automated mechanised tamping machines [37].

Today, combined levelling, lining and tamping machines, that make it possible to tamp up to four sleepers at the same time, are state of the art.

Within the actual tamping process, the tamping unit of the machine is centrally positioned above the sleeper. Afterwards, a lifting and lining unit raises the track and simultaneously displaces it laterally to the desired position which was determined in the pre-measuring process. Next, the constantly vibrating tamping tines penetrate the ballast bed and, after the final depth is reached, the squeezing movement starts. Rising pressure in the hydraulics close the tamping tines and compacts the ballast underneath the sleepers. Afterwards, the tines open and the tamping unit is lifted. Figure 5 gives a graphical overview of the different stages of the tamping process. The squeezing procedure is carried out one to three times, depending on ballast condition and required lifting values [12]. Today, continuously working tamping machines are state of the art. This means the whole machine moves continuously forward at a certain speed and only the aggregate frame with the tamping tines stops for executing the tamping process. In contrast to that, older machines work cyclically. Thus, the whole machine has to stop for the tamping task and move on to carry out the work at the next sleeper [34].

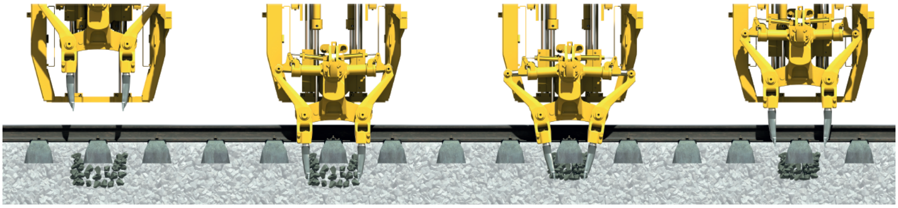


Figure 5: Different stages of a tamping process [34].

The quality and success of a tamping action depend on many factors. Some of them are within the scope of the machine and can be influenced by adjustments to them. The most important tamping parameters are [4]:

- Frequency (35 Hz)
- Amplitude (4 – 5 mm)
- Lifting height (minimum and maximum values have to be considered)
- Tamping depth
- Squeezing velocity
- Squeezing time (0.8 – 1.2 sec)
- Tamping force (10 – 12 kN)

Today, for line tamping, tamping machines are used which make it possible to tamp one, two, three or four sleepers at the same time. The type of the tamping machine has significant influence on the working speed. With a modern four-sleeper tamping machine, up to 2,600 m of track can be treated per hour [38]. Figure 6 shows a four-sleeper tamping machine with an electric power supply as an example.

Figure 6: Four-sleeper tamping machine “Dynamic Stopfexpress 09-4X E^3” [39].

It must be mentioned that it is not reasonable to consider working speed as the only criteria for utilising a specific tamping machine. It is much more important to choose the right machine for the given boundary conditions (chapter 12.4). For example, a high-performance four-sleeper tamping machine is suitable for long sections without any hindrances but is not the right choice for treating turnouts or single failures surrounded by good track quality. In these cases, one-sleeper tamping machines that provide the necessary flexibility and are specially designed for these areas of application should be used.

Immediately after the tamping task has been carried out, the resulting track geometry is checked through the tamping machine. Within this process, longitudinal and horizontal level, twist, cross level and tamping parameters like lifting values and squeezing time are recorded and documented. Based on these data, the customer then evaluates and accepts the executed work [40].

In Austria, besides a tamping machine, a track profile together with a ballast distribution system and a dynamic track stabilisation are also used one after the other. This machine configuration is called “track refurbishing train”. The advantage it offers is that all necessary tasks can be executed within one work step, and only one temporary track closure is required. One example for this is shown in Figure 7.

Figure 7: Track refurbishing train: tamping machine, ballast distribution system, dynamic track stabilisation [41].

The ballast distribution system is responsible for profiling the bedding to create an even cross section and for removing excess ballast on the track. Some systems are equipped with ballast reservoirs so that they can collect excess ballast and re-distribute it to areas where it is needed [4].

A dynamic track stabiliser initiates lateral oscillation of the track grid while contemporaneously applying vertical strains. Through this procedure, initial settlements are anticipated in a controlled manner. This leads to a significant improvement of resistance to lateral and longitudinal displacements. Furthermore, the ballast bed is homogenised in a vertical direction and sleeper cavities are reduced. Hence, more durable track quality is achieved [4] [42].

Modern high-performance tamping machinery (Figure 6) already contains dynamic track stabilisation. In these cases, the track refurbishing train only consists of two machines. The most innovative machine configuration used in Austria is the “MDZ 3000”. This refurbishing train includes the continuous four-sleeper tamping machine “Dynamic 09-4X” with integrated track stabilisation followed by the ballast distribution system BDS 2000 [43]. This configuration is shown in Figure 8.

Figure 8: MDZ 3000: Dynamic 09-4X and BDS 2000 [41].

3.1.2 Spot tamping

Isolated track geometry defects surrounded by areas of good track quality are called single failures. When correcting them, it would not be reasonable to utilise a big line tamping machine or even a track refurbishing train.

This machinery is intended to execute track geometry correction on longer sections.

Thus, for the removal of single failures, spot tamping is executed, which means performing a tamping task within a close area of the failure [44]. In contrast to line tamping actions, where the track geometry is restored to the absolute nominal position, within a single failure removal, the track geometry is corrected to a relative level. This means the track position within the single failure is adjusted to the surrounding track geometry without considering the deviation from the absolute position.

In practice, there is a variety of different methods used for repairing single failures. The bandwidth ranges from manual tamping with hand-held devices right up to lightweight tamping machines like manually pushed machines, small self-propelled machines or attached tamping units and special spot tamping machines (Figure 9) [12]. Depending on the method used, the processes of pre- and post-measuring as well as the tamping procedure itself are also very diverse.

In Austria, in most cases, specific tamping machines like UNIMAT (Sprinter) are used for the removal of single failures. These one-sleeper tamping machines are designed for applications where a high degree of flexibility is required. Therefore, these machines are also used for tamping turnouts and crossings [45]. The tamping procedure itself works the same way as with line tamping machinery. The biggest difference lies in the pre-measuring process. On the one hand, track geometry correction within spot tamping is executed to a relative level and therefore, no reference to any absolute position is required. On the other hand, modern spot tamping machinery is equipped with special measuring and software systems [46] that make it possible to determine the required correction values during the working process. Thus, in most cases, a separate pre-measurement can be omitted and no additional temporary track closure is therefore required. This is also true for the post-measuring process, as the measuring system records all relevant values for acceptance control.

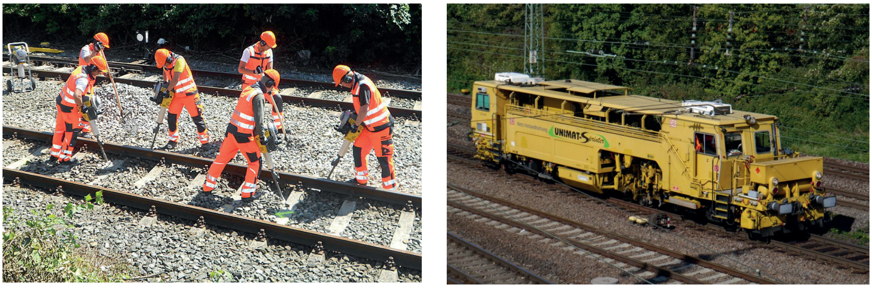


Figure 9: Spot tamping with hand-held devices (left [47]) and the tamping machine UNIMAT Sprinter (right [48]).

As experiences have shown that single failures often return to the same position relatively quickly after the correction, “design tamping” was initiated. “Design tamping” is a special means of adjusting the track to a relative level, following the idea of achieving the optimum track level after the initial settlement process. Design tamping is done by uplifting the track to a higher level, which creates some reserve in height for the settlement [4] [49].

3.2 Ballast cleaning

In the event of an excessively fouled ballast bed, its tasks can no longer be performed sufficiently. In these cases, tamping shows no significant positive effect anymore or the restored track quality deteriorates quite quickly after the measure has been carried out. Once such a condition is reached, complex measures like ballast cleaning are necessary. In Austria, ballast cleaning is not a standard maintenance task but rather is executed within a total track renewal. Nevertheless, in some cases – especially for tracks with a long remaining service life expectancy – ballast cleaning might be reasonable in form of a maintenance task [50].

Nowadays, high performance machinery is utilised for ballast cleaning measures in Austria (Figure 10, right). These machines are equipped with a flexible excavating chain that removes the ballast material (Figure 10, left). Via a conveyor belt system, the material is transported to the sieving plant of the machine. Here, the still usable ballast material is separated from the oversize and undersize particles. After the sieving process, the recycled ballast is reinstalled together with fresh ballast. The amount of re-usable material depends on the degree of contamination and the weather conditions. In case of highly fouled ballast and/or poor weather conditions, it might be necessary to perform a total excavation. This means that the whole ballast material has to be replaced by new ballast.

Figure 10: Excavating process on the construction site (left [51]) and ballast cleaning machine RM 80 UHR (right [52]).

The removal of the fouled ballast as well as the transport of the fresh ballast to the construction site is performed by means of so-called material conveyor and hopper units (MFS) [40].

These wagons are connected through conveyor belts with the ballast cleaning machine to guarantee an optimal flow of the materials. After ballast cleaning, it is necessary to tamp the treated section several times to guarantee full operability of the track [53]. It has to be mentioned that ballast cleaning is, to a great extent, a line construction project. This means the issues of logistics and material flow must be given special attention.

Ballast cleaning machinery can be also used in turnouts. Therefore, some adaptions (gradual broadening) on the excavating units are necessary. Ballast cleaning machinery for turnouts of the newest generation uses a pivoted sword to excavate the material [54].

In Austria, the standard machine for ballast cleaning is the RM 80 UHR (Figure 10, right). This is a standard ballast cleaning machine with an adjustable excavation chain and one sieving unit. It can be used for ballast cleaning as a maintenance task and also within the construction workflow of a total renewal [55]. Another machine used is the RU 800 S, which is a combined ballast cleaning and track renewal machine. This means, in addition to ballast cleaning, the machine makes it possible to exchange rails and sleepers in a single work step [56]. New high-performance machinery is constructed modularly and can be additionally equipped with more than one sieving plant, a washing system for the ballast material together with a water recycling system, a crushing plant or a star screen [57].

3.3 Subsoil rehabilitation

Poor track quality and track geometry issues cannot always be traced back exclusively to a fouled ballast bed. Track formation and subsoil also have significant influence on durable track quality. This is especially true, as traffic loads are constantly rising and therefore the requirements on subsoil are increasing, too [40]. However, because of the high degree of effort and costs involved in mechanised subsoil rehabilitation, it is not executed as a standard maintenance task. That said, it might be quite a useful option to execute subsoil rehabilitation in conjunction with a track renewal in the event of poor subsoil conditions, as this makes it possible to prolong service life and significantly reduce maintenance requirements [58].

For assessing the subsoil condition, innovative analysing systems like fractal analyses of vertical track geometry or ground-penetrating radar can be used. For a detailed evaluation, geotechnical surveys are necessary, which is quite expensive and time-consuming [59].

If insufficient subsoil conditions are detected, subsoil rehabilitation can be performed conventionally by means of an excavator. However, nowadays, subsoil rehabilitation is mostly performed with fully automated, track-bound machinery systems.

The main objective of such a subsoil rehabilitation is the installation of a formation protection layer that consists of a mixture of sand and gravel. The thickness of the layer depends on the bearing capacity of the natural ground. Additionally, during the rehabilitation, geotextiles and appropriate drainage equipment are also installed [4].

In Austria, the machinery system AHM 800 R (Figure 11) is mainly used for the task of subsoil rehabilitation. This unit is equipped with two excavation chains – one for the ballast and one for the formation layer and soil. The first chain removes the upper ballast layer and the material is subsequently crushed. Afterwards, the crushed material along with the appropriate coarse gravel and water is processed into a substance for a protection/bearing layer and transported to the installation site. After unloading the material, it is distributed homogeneously, levelled and compacted. This means parts of the excavated ballast can be re-used within the new track formation layer [60] [61]. Some subsoil rehabilitation machines are also able to re-use (parts of) the removed material as track ballast. Furthermore, the considered machines have the ability to continuously install geotextiles [62].

Figure 11: AHM 800 R in use on a construction site [63].

The latest innovation in the field of subsoil rehabilitation is the machine PM 1000 URM, which is equipped with three excavation chains. This machine makes it possible to install up to five different layers and focuses on the optimised re-use of the removed material [40]. The machine has a total length of 270 m [64].

4

Planning of tamping tasks – an overview

The previous chapters underlined the great importance of tamping tasks for ballasted tracks. However, compared to other complex measures like ballast cleaning, for example, one single tamping task seems much simpler and cheaper to execute. Under these circumstances, there is the risk that the possible consequences of tamping measures may be underestimated. That said, as the following chapters will show, the process of planning tamping tasks is quite a challenging one, as the intensity of execution is much higher compared to other measures. This means the single measure is not that expensive but, because of the frequency, the total budget required for tamping actions is quite high. Furthermore, performing tamping tasks at the right time can have a significantly positive influence on the service life of the track. On the other hand, executing measures at the wrong time runs the risk of shortening the service life. In summary, this means that the right tamping strategy has substantial influence on a track's service life, and therefore great attention should be paid to the planning of tamping tasks so as to optimise not only maintenance but also the life cycle costs of the track.

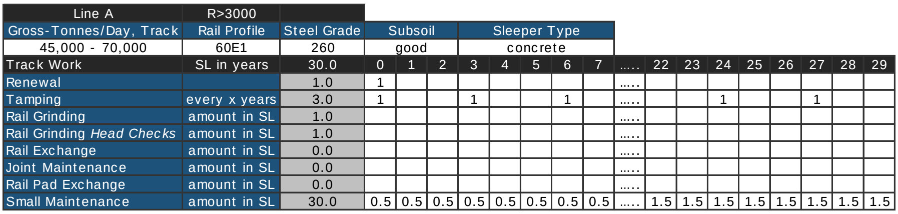
The present chapter should give an overview of the different possibilities for planning tamping tasks. Therefore, in the beginning, the strategic approach of standard elements is introduced. Furthermore, the current situation of tamping measures in Austria is presented and analysed. Moreover, different approaches for planning tamping actions from practice and literature are described and discussed. The results of these investigations should demonstrate the missing aspects in the previous considerations and highlight the research goals, questions and demands for the present thesis.

4.1 Standard elements – strategic approach

By observing a whole railway network, it must be considered that one asset type can exhibit quite different properties. This is especially true when dealing with an inhomogeneous network as it exists in Austria. Contemplating a railway track, the assets exhibit significant differences in superstructure configuration (sleeper type, rail type, rail steel grade), traffic load, radii, subsoil condition and the number of parallel tracks. The various characteristics of these attributes lead to different life spans and maintenance intervals and, as a consequence, to widely differing life cycles and life cycle costs for different track sections [65]. One specific combination of the parameters described above is designated as a standard element. Theoretically, there would be very many opportunities to combine the parameters. However, many of them do not exist in practice and therefore about 50 standard elements are able to describe 90% of the entire network in Austria [30].

Subsequently, for every reasonable parameter set – i.e. for every reasonable standard element – a working cycle was developed. This working cycle describes the strategic service life together with an average maintenance regime which is necessary for the given characteristics. The input data stem from data warehouses of the infrastructure manager, expert knowledge and field experience. In addition to the track, standard elements were set up for many other assets (e.g. turnouts, bridges, railway crossings) [58] but as they are outside the scope of the present thesis, they are not addressed further. Figure 12 shows a standard element (first three lines) alongside its associated working cycle. In this example, the parameter combination exhibits a service life of 30 years and a tamping cycle of three years. It must be strongly emphasised that these values represent an average across the network and cannot be directly applied to single sections. In a subsequent step, the necessary tasks can be multiplied with their specific costs to calculate the life cycle costs for the given boundary conditions.

The standard element approach was first established in Austria as part of a cooperation between TU Graz and ÖBB. The approach is also used in Switzerland (SBB), Croatia (HZ) and Sweden (TVK). Other infrastructure managers use similar approaches too [30].



Line A	R>3000																		
Gross-Tonnes/Day, Track	Rail Profile	Steel Grade	Subsoil			Sleeper Type													
45,000 - 70,000	60E1	260	good			concrete													
Track Work	SL in years	30.0	0	1	2	3	4	5	6	7	.....	22	23	24	25	26	27	28	29
Renewal		1.0	1								.....								
Tamping	every x years	3.0	1			1			1		.....			1			1		
Rail Grinding	amount in SL	1.0									.....								
Rail Grinding *Head Checks*	amount in SL	1.0									.....								
Rail Exchange	amount in SL	0.0									.....								
Joint Maintenance	amount in SL	0.0									.....								
Rail Pad Exchange	amount in SL	0.0									.....								
Small Maintenance	amount in SL	30.0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	.....	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5

Figure 12: Example for a standard element and the associated working cycle.

Standard elements are very helpful tools for the following tasks that can have significant influence on tamping strategies [30]:

- Maintenance and renewal demand
  By merging the different standard elements with the real railway network, the annual strategic amounts for maintenance and renewal can be determined. By combining the amounts with the related costs, it is possible to estimate budgets for the different tasks. This means that standard elements allow for the derivation of annual lengths as well as budgets which are necessary for tamping over the network.
- LCC-based decision making
  As the average maintenance regimes together with their related costs are known for different boundary conditions, it is also possible to compare different component and maintenance strategies. This means the influence of varying components on the service life and the tamping demand can be examined. Furthermore, the consequences of reduced or increased tamping intervals can be analysed.

In sum, standard elements allow for the determination of overall amounts and the support of developing strategies over the network. However, it is important to say that this strategic approach does not allow for maintenance planning in the proper sense. For planning tamping tasks on specific sections, it is indispensable to evaluate the real condition within the considered area.

4.2 Tamping tasks in reality

This chapter should give a brief overview about the tamping activities in the Austrian railway network. The first parameter that is of great interest is the total amount of tamping kilometres per year. Figure 13 shows the tamping kilometres between 1999 and 2017 for the lines that are contained in the TUG database (chapter 6.3.1). This data warehouse covers about 4,400 km track kilometres of the Austrian railway network. The examination contains only line tamping in the form of maintenance.

This means tamping for single failures or turnouts and tamping tasks executed as part of track renewal, ballast cleaning or subsoil rehabilitation are not included.

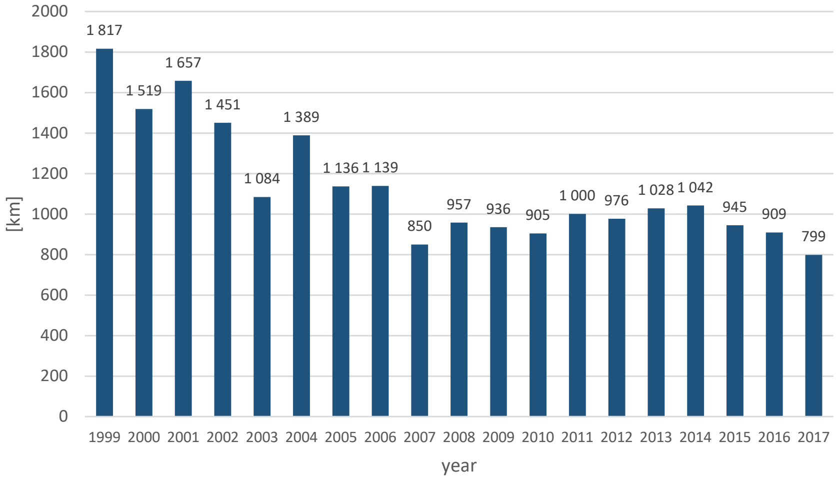


Figure 13: Amount of tamping measures between 1999 and 2017 within TUG-DB.

The evaluation shows that tamping quantities decreased significantly from 1999 to 2007. Exceptions are only visible in 2001 and 2004. After 2007, a slight increase can be observed until 2014. Since then, the tamping kilometres per year have been in decline again. Former studies [66] show quite similar results and additionally demonstrate that a global reduction of tamping kilometres leads to a network-wide deterioration of track quality – at least on a short-term scale. This topic is discussed later in much greater detail in chapter 8.

Considering all tamping tasks between 1999 and 2017 and the length of the network (4,400 km), an overall tamping interval of 3.89 can be calculated. This means that network-wide, every 3.89 years a tamping task is executed for each section on average.

Another interesting parameter regarding tamping tasks is the length of a continuous measure. For examining this, a representative line for the Austrian railway network is chosen. The line has a length of about 250 km and covers all relevant boundary conditions like different superstructure, substructure, track age, axle loads, traffic loads and speeds. For this line, all the executed continuous tamping actions (again without spot tamping, tamping of turnouts and tamping tasks as part of renewal, ballast cleaning or subsoil rehabilitation) between 2005 and 2015 are analysed. Figure 14 shows the results and indicates that the largest section lengths were executed between 2005 and 2007.

Between 2008 and 2010 the lengths decreased to about 500 m on average and raised to about 700 m in 2011. Afterwards a decrease of the section length can be noticed every year. Furthermore, the evaluation shows that working lengths of more than 1,500 m are the exception. Considering all tamping tasks within the evaluation, an average section length of 520 m can be indicated.

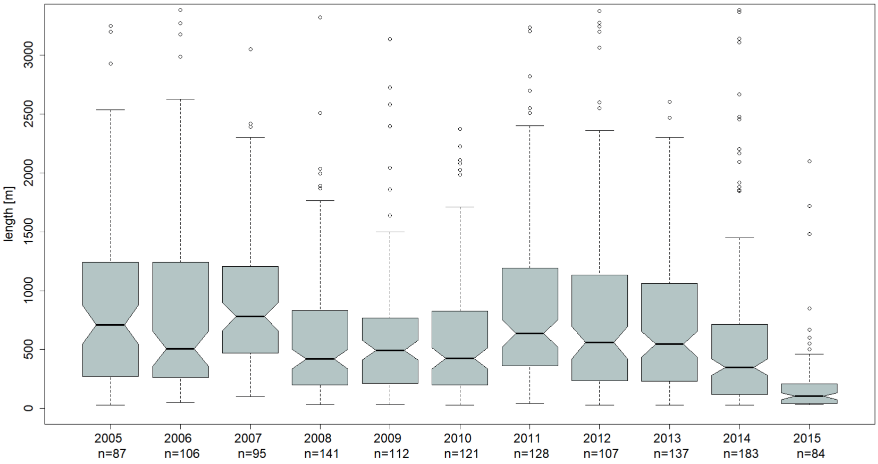


Figure 14: Length of tamping actions between 2005 and 2015 on a representative sample line.

Besides the analysis of executed tamping actions, it is also of great interest to draw a comparison between tasks actually performed and strategic amounts, indicated by standard elements. In order to examine this, a special investigation was carried out by Fellinger [67] [68]. As a first step, the tamping intervals (TI) were determined for the whole network which is covered by the TUG data warehouse (chapter 6.3.1). The results are depicted in Figure 15 and are indicated for different classes of traffic loads (LC) separately.

As such, the classification is based on the daily gross tons per track. The investigations show a relationship between the traffic load and the tamping interval: The higher the traffic load is, the more often tamping actions are executed, which is reflected in a lower tamping interval. LC5 is the only exception, showing lower tamping intervals than tracks with higher loads. On average, the examination displays a tamping interval of 3.9 years over the entire network, which clearly confirms the results of the present evaluations (Figure 13).

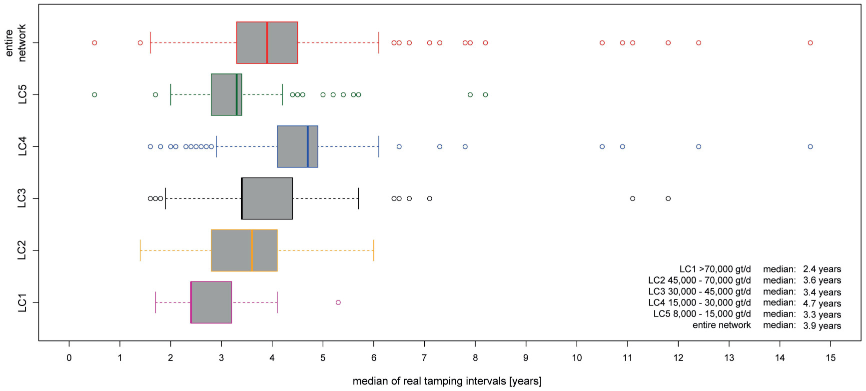


Figure 15: Network-wide evaluation of real tamping intervals (median), according to [67].

In a subsequent step, tamping intervals actually performed are compared with tamping intervals, indicated by the related standard elements. The comprehensive evaluation for all considered sections shows that about one third exhibits quite similar, one third lower and one third denser tamping intervals than the standard element. More detailed results of this analysis are depicted in Figure 16 – again for the different traffic load classes – and show a clear correlation: The lower the traffic load is, the lower the tamping intervals are compared to the standard element. In other words, it can be stated that lower traffic load classes (LC5, LC4, LC3) exhibit lower tamping intervals than the standard element indicates. This means tamping actions are carried out more often than the strategic amount in the standard element specifies. For the higher load classes (LC2, LC1), the evaluation shows exactly the opposite. Within these load classes the executed tamping intervals are longer and the actually performed amounts are lower than the standard element determines.

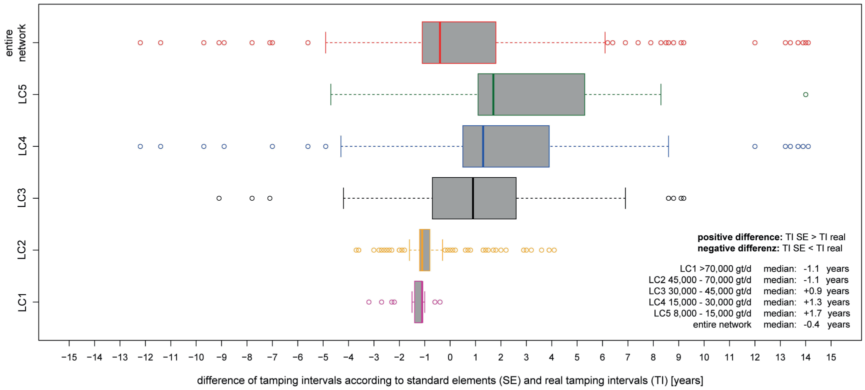


Figure 16: Network-wide evaluation of differences in tamping intervals according to standard elements and real tamping intervals, according to [67].

The overall result for the entire network is particularly noteworthy, with a deviation of only -0.4. This means that, across the whole network, the tamping intervals actually executed and those indicated by the standard elements are quite similar. This and the above-mentioned results impressively emphasise the reasonable use case for standard elements: They are intended for the determination of strategic, network-wide amounts and budgets. The strategic amounts of standard elements should not be transferred to single track sections. In case of planning tamping tasks for specific areas, sophisticated technical and economical evaluations are necessary that address the boundary conditions of the considered section. As this is quite a challenging issue, a further focus of this thesis shall be all the topics necessary to fulfil these tasks and to create an operative tamping schedule.

4.3 Existing tamping scheduling tools and approaches

Planning maintenance tasks in order to guarantee safe and comfortable railway operation and to use the budgets in the most reasonable way is one of the core tasks of every infrastructure manager. Therefore, various tools and approaches were developed to support this process. The present chapter gives an overview of existing maintenance planning tools and scheduling concepts and describes their most important properties.

In Austria, New Austrian Track Analysing System (NATAS) [69] is widely used for this purpose. NATAS is not a maintenance planning tool in the narrower sense. It is primarily a format for visualising measuring data that is widely used and can form the basis for planning maintenance tasks. NATAS sheets contain a track section of 5 km, and five different sheets are available for every 5 km section.

The length of 5 km is fixed and cannot be adapted to longer or shorter sections. Besides all the relevant signals from the measuring car, information regarding the superstructure, special assets (e.g. bridges, turnouts, railway crossings), line characteristics (curvature, speed), executed maintenance tasks and subsoil condition are provided by the five sheets. NATAS mainly contains data from the last measuring run. Historical data are only available for a few signals and a few past measurement runs. As NATAS sheets are visual tools, it is not possible to carry out any data analyses with this system. Hence, it is also not possible to develop or apply any prognosis models by means of NATAS to predict future maintenance tasks automatically. An example of one NATAS sheet for a 5 km track section is depicted in Figure 17.

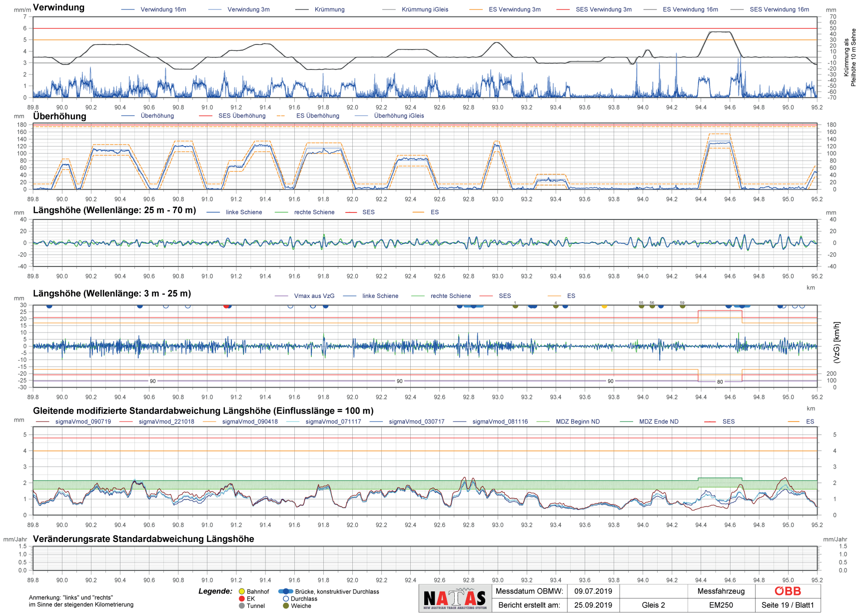


Figure 17: Example for NATAS sheet from ÖBB.

Over the last few years, several maintenance decision supporting systems like IRISSYS from ERDMANN-Softwaregesellschaft mbH [70], Optram from Bentley Systems Incorporated [71] or RAMSYS from MER MEC S.p.A. [72] were developed. The main tasks of such systems include the visualisation of various pieces of information and supporting the maintenance planning process for the user. These platforms are mostly modular in design and can be adapted to meet the specific needs of the user.

One well documented example for this is swissTAMP [73], where the Swiss Federal Railways (SBB) set up a maintenance support system based on IRISSYS.

In this case, the basic functions of the program are adapted and SBB themselves develop methodologies for data analysis and maintenance planning according to their requirements which are included in the platform. The basic contents of such systems are quite similar to NATAS. This means they may incorporate measuring data, information regarding the superstructure, special assets and the line characteristic as well as past maintenance actions. It is important to note that the platforms just build a framework that has to be equipped with data by the user. As a result, the usability of the system highly depends on the quality and reliability of the added data. Compared to NATAS, such systems are designed more dynamically. This means that the length of the considered track section as well as the desired information can be selected by the user (e.g. longitudinal level of the last five measuring runs together with curvature and line speed from km 3.000 to km 5.270). An example for such a report generated from IRISSYS shows Figure 18. Furthermore, the systems may include possibilities to predict future quality behaviour and maintenance tasks. Here it must be highlighted that the forecasts can only be as good as the incorporated prediction models and algorithms. This means they have to be developed and verified in advance, as the decision support systems are not intended for creating models or data analyses on a large scale.

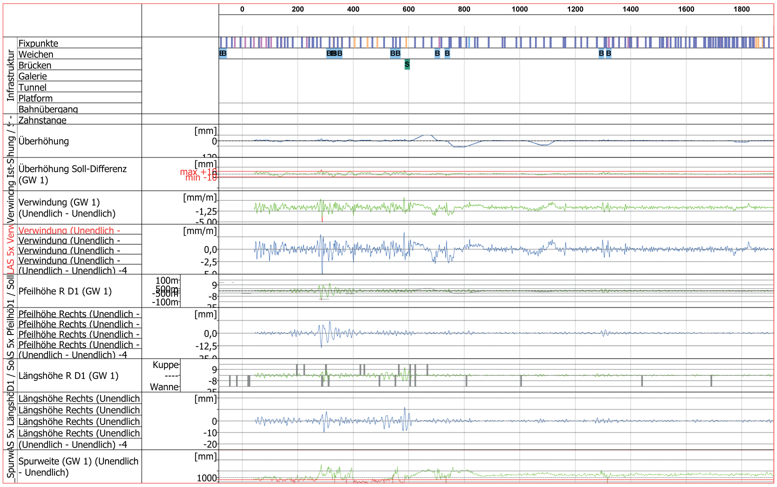


Figure 18: Report generated from IRISSYS.

Maintenance scheduling is a field that is also treated in several research works. In the following, a review of different academic approaches is shown, whereby the focus is set on the planning of tamping tasks.

The goal of Miwa [74] is to develop a mathematical programming model for the allocation of a multiple-sleeper tamping machine. The model should optimise both maintenance costs and track quality. Thus, various constraints like the location of depots, location of lots that have to be tamped or the frequency of tamping in one lot can be considered. For the case study, the test section is divided into segments with a length of 500 m.

Famurewa et al. [75] set the focus on optimum allocation and efficient utilisation of track possession times. In the first step, track quality behaviour is modelled with a deterioration and a recovery model for sections of 200 m. Afterwards, an optimised tamping schedule is created for a short-term period of the next two years. This is done by minimising total costs for intervention including costs of track possession while geometry quality is ascertained to be within desirable limit.

Caetano et al. [76] develop a track geometry deterioration model that considers uncertainties by defining a track geometry reliability parameter. This model is applied to track sections with a length of 200 m. In a further step, the developed model is integrated in a multi-objective optimisation model that should find the most reasonable trade-off between costs (maintenance and inspection costs) and reliability. The presented approach can help reach a desired track geometry performance and guarantee effective maintenance investments.

Within the studies from Vale et al. [77] [78], a mixed 0-1 linear program is formulated to optimise tamping operations for fixed 200 m sections. Within the model, the current track quality, the deterioration of track quality over time, recovery of track quality after tamping, track layout and limit values for track quality are considered. The optimisation goal is to minimise the number of tamping interventions within a time horizon of two years. Finally, the model is improved and expanded by Gustavsson [79].

Wen et al. [80] formulate a Mixed Integer Linear Programming (MILP) model to optimise tamping tasks for track sections of 200 m. The objective is to minimise the net present costs over a planning horizon (e.g. 3 to 4 years) within a specific area. For the formulation of the model, technical issues like track quality, a linear deterioration model, limit values, a recovery model after a maintenance task and track alignment are considered. Furthermore, the model contains economical parameters like tamping costs, driving costs and preparation costs as well as a discount rate to calculate the net present costs.

Zhang et al. [81] develop a model for maintenance scheduling based on an enhanced genetic algorithm approach. Therefore, uncertainties within the deterioration process, the safety of transportation service, the lifetime loss of the replaced track, the maintenance costs and the travel costs are considered. The goal is to find the maintenance schedule that minimises the overall costs within a finite planning horizon.

Quiroga et al. [82] [83] present an heuristic approach where tamping measures are scheduled on a long term scale. The basic inputs are deterioration and restoration models for track quality [84] together with available resources. The result is a list of scheduled tamping tasks for each considered 200 m segment for the whole life cycle together with the development of track quality over time. These outputs should help to compare different maintenance strategies and to find the most reasonable one.

Rhayama et al. [85] present an approach that quantifies uncertainties of track parameters/layers that are responsible for track quality behaviour and as a consequence for the execution of maintenance tasks. Therefore, stochastic finite elements (SFE) method is used. The goal of this work is to estimate track quality (behaviour) after a maintenance action. This should allow for the comparison of different possible maintenance tasks and for choosing the most reasonable one.

Chrismer et al. [86] previously calculate the track settlement from ballast, sub-ballast and subgrade and relate it to differential settlements (track roughness). Subsequently, the future development in track roughness is calculated and any exceedances of specified limits are detected. Furthermore, a costing model gives an overview of different maintenance options and their influence on the life cycle costs of the asset.

Andrews [87] investigates track quality behaviour over time and calculates degradation distributions as an initial step. With these distributions, a track section model is formed which incorporates the maintenance and renewal process and provides the possibility to predict the condition of the ballast section over time. The model uses a Petri net formulation with a Monte Carlo solution routine. It makes it possible to analyse the effectiveness of different maintenance strategies.

4.4 Summary and problem definition

In section 4.3, various approaches for planning maintenance tasks are introduced. By examining them, it becomes apparent that many problems are solved quite similarly and great differences can be observed in other points.

Most of the analysed studies show an approach that optimises tamping scheduling regarding a specific target function by means of a mathematical model. Some studies show solutions for very detailed problems, while some show more general approaches. However, it has to be stated that some challenges in the context of planning tamping tasks are still unsolved or only tackled too superficially for developing a reliable maintenance plan. These points are to be discussed below.

The basis for any maintenance schedule for the upcoming years is a reliable model that describes track quality deterioration as well as the restoration of track geometry after a tamping intervention. By analysing the approaches, it turns out that the models used for track quality degradation are different – especially linear, logarithmic and exponential models are used. Nevertheless, all these models are established and can be found in various literature sources. Concerning recovery models, the situation looks a little bit different. In most studies this topic is not considered or only very simplified models and approaches are used that contain only a few relevant parameters. Furthermore, the development of track quality deterioration rates over time is considered insufficiently (e.g. same degradation rate in every deterioration period).

Another point that is quite similar in all analysed cases is the segmentation of the track in fixed sections – mostly with a length of 200 m. This implies that only one track quality figure is calculated for each 200 m section, and thus various track geometry phenomena within this section are mixed up. This can lead to misinterpretations, especially in the case of calculating time series, which is a core element of maintenance planning. Furthermore, the separation into fixed sections means that only these areas can be considered and therefore maintained as a whole. This leads to a major loss in flexibility and to a situation in which areas are maintained where no maintenance was necessary and vice versa.

Furthermore, due to the fixed segmentation, it is not possible to consider any possible influence of special assets (e.g. turnouts, bridges) on the generation of reasonable lengths. These assets often mean logical starting or end points of maintenance tasks and are therefore of great importance in creating tamping sections.

Another shortcoming that can be observed in existing approaches is revealed in the planning horizon. In most cases, only the next intervention or a few upcoming years are considered. This leads to optimisations for only short time spans without the consideration of mid- to long-term effects on track quality and life cycle costs.

A very important parameter within the planning of maintenance tasks is the intervention level (ILE). Choosing an optimal intervention level consists a lot of potential to extend tamping intervals and service life for reducing life cycle costs. However, most of the analysed approaches use constant intervention levels or very simplified methods to calculate them. The influence of the intervention level on more than the next period is missing in most cases. This makes it quite difficult to optimise the maintenance schedule regarding the life cycle and the related costs.

The presented approaches try to optimise maintenance schedules by means of one or a few optimisation criteria.

Conversely, this implies that many other parameters that are relevant for maintenance planning are neglected. Hence, there is a need for a holistic approach that considers all relevant factors. This also means that a certain flexibility is missing for adapting the maintenance schedule to the specific needs of the user. This would be quite important as under different circumstances, the goals of the user can vary.

In some cases – especially at the end of the service life – tamping is no longer the right measure, as the degree of ballast pollution is already high. In these cases, tamping cannot deliver a durable track quality anymore, and more complex measures like ballast cleaning have to be executed. Most of the analysed approaches do not deal with this topic, and finding a reasonable alternative for tamping is outside the scope of the research.

Based on the analyses above, the present approach develops a tamping schedule that counteracts the described shortcomings and fulfils the following requirements:

- Track quality should be described in an appropriate way with an established quality figure.
- Track quality behaviour over time must be described and predicted by means of reliable models. To determine these models, measuring data for all relevant boundary conditions over long time series should be used.
- The effects of a tamping intervention and the restoration process have to be known.
- An optimal intervention level should be found, and the influence of any intervention level on the service life of the track should be evaluated.
- A developed tamping schedule should be as flexible as possible. This means fixed sections are avoided and the calculations are executed with sliding windows.
- The developed maintenance plan must be technically executable.
- Besides technical issues, economical and operational parameters should also be considered.

- The developed model should give the user the possibility to optimise the schedule on the basis of specific boundary conditions and not only on the basis of predefined parameters.
- The economic consequences of executing the developed tamping schedule should be known together with the monetary advantages and disadvantages of other options.
- In case of poor track quality, where tamping is no longer the right measure, alternative reasonable possibilities should be demonstrated.

5

Track quality

As mentioned in chapter 3, tamping tasks have to be executed in case of inappropriate track quality, which can be expressed by track geometry parameters. For the planning of tamping actions, this means that detailed, in-depth knowledge of track geometry and their influencing parameters is required. For this reason, it is the goal of the present chapter to analyse different possibilities for recording, describing and investigating track quality. Since there are many different approaches to characterising track quality, the most suitable one for planning tamping interventions shall ultimately be found.

5.1 Track measurement car

For recording track geometry, nowadays, so-called track measurement cars are utilised. In Austria, track measurement cars [88] (Figure 19) assess track geometry of the whole network two to four times a year. This approach allows for objective measurements which are generated at high speeds (in Austria theoretically up to 250 km/h). Furthermore, these measurements can be executed continuously and regularly on a network-wide basis. The basic measurement equipment on measuring cars of this kind are as follows:

- Track geometry (including gauge)
- Axle bearing acceleration
- Rail profile
- Rail surface scans

Figure 19: Measuring car from ÖBB “Rail Checker” [89].

With the help of these systems, many measuring signals are recorded, such as vertical and horizontal track geometry, twist, cant, gauge, several accelerations, rail inclination, rail foot distance, equivalent conicity, rail surface, rail side wear, rail height wear, curvature and longitudinal inclination.

Additional possible measuring systems include ultrasonic, eddy-current or catenary measuring systems, ground-penetrating-radar devices and lidar-scanner. In Austria, these additional systems are not mounted onto the standard measuring car but are executed via separate vehicles/devices.

For the purposes of the present thesis, the most relevant system is the track geometry measurement unit. For recording track geometry, two principles of measurement exist: the chord measurement system and the inertial measurement system. Within the chord measurement, the measured and the nominal versines are compared and evaluated. As the versines depend on the wave length of the geometry error, a transfer function is required for determining the real track geometry failure [90]. Nowadays, in Austria, recording track geometry (POS/TG Position-Track Geometry Measurement System) is performed by an inertial measurement unit (IMU), two optical gauge measurement systems (dual OGMS) and a navigation system (navigation computer with integrated GPS receiver and GPS antenna). For the measurement, a measurement framework is coupled to the four axles of the chassis, and the four sensors for the doubled gauge measurement are attached. The measurement framework guarantees a constant parallel alignment of the sensors and the IMU in relation to the rail surface, and thus it can be used as a reference level for the geometry measurements. With the three acetometers and the three rotatory encoders which measure angular changes, it is possible to describe the motion as a 3D curve in relation to geographical coordinates. The recording of angular changes is executed by means of three optical gyroscopes.

Thus, the system captures the translational and rotational motions. These motions can be integrated twice to calculate the location of the recording vehicle and the track. By measuring the track gauge, the 3D-curve can be calculated separately for each rail. Based on the 3D-curve, all desired track geometry data can be obtained, saved and retrieved [88].

Assigning the recorded data to the related track kilometre with an appropriate accuracy in terms of reproducibility and repeatability represents quite a challenging task. Therefore, the system GALS (GPS Aided Location System) is used, which combines data from differential GPS systems with data from the POS/TG. The utilised Integrated Inertial Navigation algorithm (IIN) enables the user to carry out the recording even during brief failures of the differential GPS and also increases the output of positional information to 200/s [91]. Based on this algorithm and the post processing of the data, a positioning accuracy can be reached that is clearly satisfactory for tamping scheduling within the open track.

5.2 Track geometry parameters

Based on the information provided by the measurement car, different track geometry parameters can be determined. EN 13848-1 [92] defines the following five principal track geometry parameters to describe track quality:

- Longitudinal level
- Alignment
- Twist
- Cross level
- Track gauge

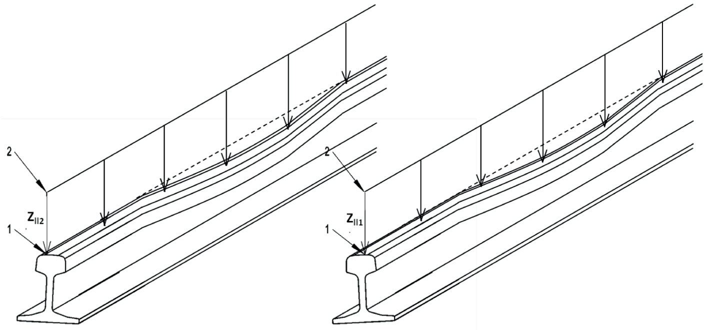
Hereafter, the five parameters are shortly introduced by means of their definitions regarding the norm EN 13848-1.

5.2.1 Longitudinal level

Longitudinal level is the deviation z_{ll} in z-direction of the running table levels on any rail from the smoothed vertical position (reference line) expressed in defined wavelength ranges (Figure 20). Smoothing is applied over a length that covers the considered wavelength range (at least two times the upper limit of the wavelength range of interest). The reference line and the longitudinal level are calculated form successive measurements.

For the calculation of longitudinal level, the three ranges of wavelength (λ) should be considered:

- D1: 3 m < λ ≤ 25 m
- D2: 25 m < λ ≤ 70 m
- D3: 70 m < λ ≤ 150 m (should only be considered for line speeds greater than 230 km/h)



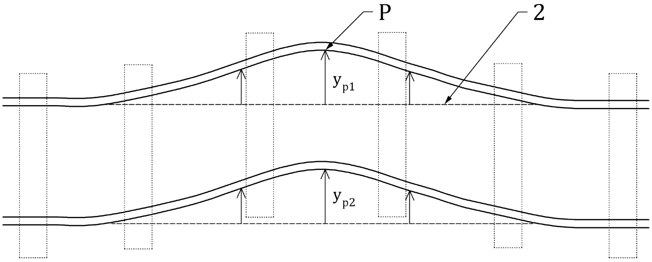
1 running table
2 reference line

Figure 20: Longitudinal level [92].

5.2.2 Alignment

Alignment is the deviation y_P in y-direction of the position of point P on any rail from the smoothed lateral position (reference line) expressed in defined wavelength ranges (Figure 21). The smoothing is applied over a length that covers the wavelength range of interest (at least two times the upper limit of the wavelength range of interest). The reference line and the alignment are calculated from successive measurements. For the calculation of alignment, the three ranges of wavelength (λ) should be considered:

- D1: 3 m < λ ≤ 25 m
- D2: 25 m < λ ≤ 70 m
- D3: 70 m < λ ≤ 200 m (should only be considered for line speeds greater than 230 km/h)

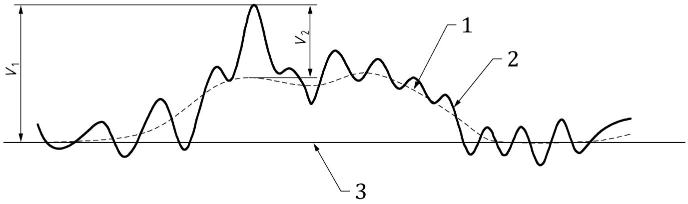


Key
P point P according to 6.1.1
2 reference line

Figure 21: Alignment [92].

5.2.3 Twist

Twist means the algebraic difference between two cross levels divided by their distance apart (base length l). It is typically expressed as mm/m. Individual defects are represented by the amplitude from the zero-line to the peak value (V_1). For purposes not related to safety issues, the mean to peak value can be used (V_2) (Figure 22).



Key
1 low pass filtered value (mean)
2 twist
3 zero line

Figure 22: Twist - Analysis method [92].

5.2.4 Cross level

Cross level (also called cant or superelevation) is the difference in height of the adjacent running tables computed from the angle between the running surface and a horizontal reference plane.

It is expressed as the height of the vertical leg of the right-angled triangle having a hypotenuse that relates to the nominal track gauge plus the width of the railhead rounded to the nearest 10 mm (Figure 23). The hypotenuse is 1,500 mm for a nominal track gauge of 1,435 mm.

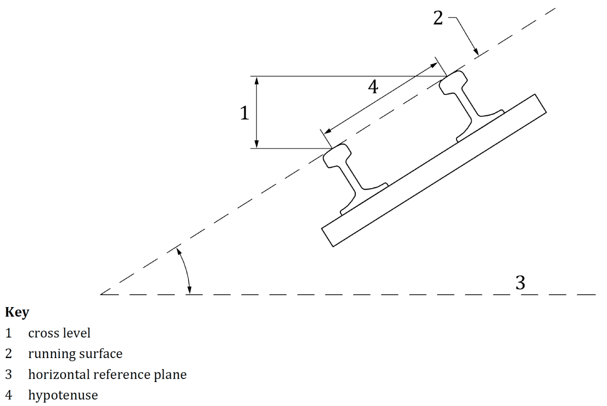


Figure 23: Cross level [92].

5.2.5 Track gauge

Track gauge (G) describes the smallest distance between lines perpendicular to the running surface intersecting each railhead profile at point P in a range from 0 to Z_P below the running surface. In [92] Z_P is always 14 mm. In the case of unworn railheads, the point P will be at the limit Z_P below the railhead (Figure 24). By contrast, in the case of worn railheads, the height of point P for the left rail can be different from the right rail.

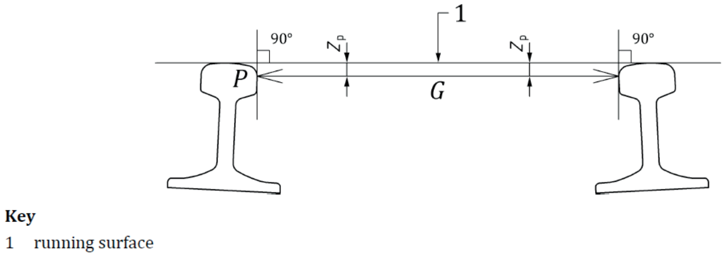


Figure 24: Track gauge for new rail [92]

5.3 Limit values and their usage for maintenance planning

Within a first step towards maintenance planning, it is possible to check the raw signals of the different track geometry parameters with regard to exceedances of intervention limits. Intervention thresholds are defined in EN 13848-5 [93], which determines the following three different limits and the corresponding measures, which have to be taken:

- Immediate Action Limit (IAL): Refers to the value, which, if exceeded, requires measures be taken in order to bring it down to an acceptable level. This can be done either by closing the line, reducing speed or by correction of track geometry.
- Intervention Limit (IL): Refers to the value, which, if exceeded, requires corrective maintenance to prevent the immediate action limit from being reached before the next inspection.
- Alert Limit (AL): Refers to the value, which, if exceeded, requires that the track geometry condition be analysed and considered in the regularly planned maintenance operations.

Limit values depend on line speed, as sections with higher speeds involve higher requirements on track geometry than sections with lower speeds. This is true because acceleration rises with increasing velocities at the same wavelength [90]. As an example, Table 1 shows immediate action limits of EN 13848-5 having normative character for the wavelength ranges (WLR) D1 (3-25m) and D2 (25-70m). In contrast to immediate action limits, AL and IL do not have normative but informative character.

Table 1: Immediate Action Limits of longitudinal level [93].

	zero to peak value [mm]	
speed [km/h]	WLR D1	WLR D2
V ≤ 80	28	N/A
80 < V ≤ 120	26	N/A
120 < V ≤ 160	23	N/A
160 < V ≤ 230	20	24
230 < V ≤ 300	16	18
300 < V ≤ 360	14	16

The actual intervention thresholds are specified in the maintenance plans of every infrastructure manager. In practice, the limit values are often defined more strictly by the respective infrastructure managers. Experiences show that the intervention levels can vary widely in different countries. For example, Austria, Germany and Switzerland show significant differences in their levels. The intervention limits in Germany and Switzerland are much stricter compared to Austria [94].

One reason for stricter limits can be higher demands on riding quality and therefore more attractive services. However, the main argument is that stricter intervention values can lead to an increase in availability as the intervention is executed at an earlier stage. Hence, the probability of unplanned speed restrictions and temporary track closures decreases. Additionally, it is not necessary to set an immediate intervention if a limit value is reached within a stricter regime [95].

Checking raw signals with regard to the exceedance of any intervention level and consequently initiating a maintenance action to remove the failure is unequivocally a very important task for every infrastructure manager to guarantee safe railway operation. Nevertheless, this is only a reactive approach where just single spots of poor track quality are detected and have to be rectified in the near future.

To establish sustainable maintenance scheduling, following this procedure alone does not go far enough. Therefore, it is necessary to generate time series that can describe track quality behaviour over time and to predict maintenance tasks in the future. Calculating appropriate time series by means of raw signals is only possible when the positioning accuracy is nearly perfect. If there are only small differences in positioning of the different measuring runs, it is not possible anymore to calculate accurate time series in one cross section. This problem can be explained by the example in Figure 25. The dashed blue line shows the signal of longitudinal level for a specific measuring run. The continuous red line shows the same signal of a measuring run five months later. As illustrated, the positioning of the two measurement runs is slightly different. Computing a time series in the black marked cross section would generate the information that there was a significant improvement in track quality at this point.

This conclusion would be completely wrong, however, since no maintenance has been carried out, but only the positioning of the measuring signal has changed slightly. Furthermore, a time series analysis would indicate a sudden degradation of track quality in the cross section where the peak of the failure is now located what is also not true.

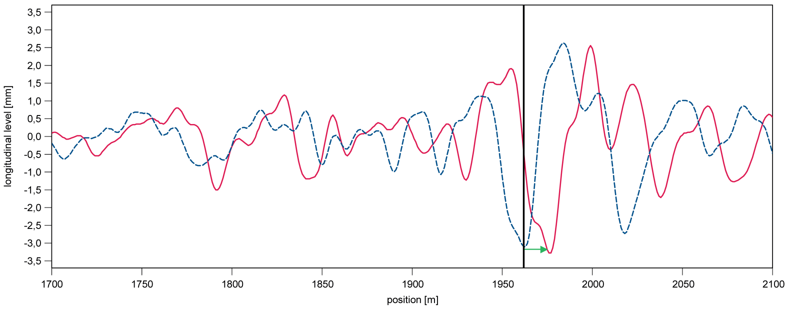


Figure 25: Raw signal of longitudinal level of two consecutive measuring runs with a positioning error.

Another shortcoming of using raw signals is that they show track quality problems only in single points which means that longer, continuous sections cannot be considered. That said, in terms of homogenous track quality and reasonable usage of available resources, it is important to execute maintenance on longer sections. Fixing single spots should be limited to defects that appear independently of the condition of surrounding areas.

In summary, this means that considering raw signals and comparing them with the related intervention thresholds is necessary to guarantee safe railway operation. Nevertheless, for sustainable maintenance planning, this approach does not go far enough, as time series analyses are hardly possible and only single spots and no continuous sections can be considered.

5.4 Track quality indices

To counteract the shortcomings of considering raw signals of single parameters, all over the world various track quality indices (TQI) were developed. These indices combine all or some of the track parameters described in chapter 5.2 in various ways to one single figure that should describe track quality in total. To encounter the disadvantages of raw signals, these quality indices often use standard deviations with a specific influence length. Within a study [96], the most relevant TQIs are analysed. Some quality indices, which are representative for the different TQI-types, are described below together with their formula.

K number

For calculating the K number, the length is determined where the standard deviations of all signals fall below a threshold value within a specific section. This calculated length is divided through the total length of the section. This means that high resulting %-values (K number) stand for sections of good track quality [97].

$$K = \frac{\sum l}{L} * 100\% \qquad (1)$$

Σl sum of section length where all standard deviations fall below the specific limit
L total length of the considered section

CN's Track Quality Index

The track quality index of Canadian National Railway Company (CN) is based on standard deviations of the track quality parameters longitudinal level, alignment (in each case separately for each rail) track gauge and cross level. For each of these parameters, a separate TQI is calculated by means of the following formula [98]:

$$\mathrm{TQI_i} = 1000 - \mathrm{C} * \mathrm{SD_i^2} \qquad (2)$$

SD_i standard deviation of a track quality parameter
C factor for considering the line class

The factor *C* considers the line class. For example, *C* assumes the value 700 for main lines. The overall quality figure is determined by calculating a mean value of the six individual indices. Higher values represent sections of better quality and vice versa [98].

$$\mathrm{TQI} = \frac{\sum_{i=1}^{6} \mathrm{TQI_i}}{6} \qquad (3)$$

Combined standard deviation

EN 13848-6 [99] proposes the use of a combined standard deviation (CoSD) for evaluating overall track quality. This quality figure contains the standard deviations of longitudinal level, alignment (each a mean value of left and right rail), gauge and cross level. Weighting factors make it possible to determine a varying degree of influence of the different parameters. The specification of the weighting factors is incumbent on the infrastructure manager.

$$\mathrm{CoSD} = \sqrt{w_{\overline{AL}} * SD^2_{\overline{AL}} + w_G * SD^2_G + w_{CL} * SD^2_{CL} + w_{\overline{LL}} * SD^2_{\overline{LL}}} \tag{4}$$

w_i	weighting factor of the parameter i
SD	standard deviation
$\overline{AL}$	alignment
G	gauge
CL	cross level
$\overline{LL}$	longitudinal level

MDZ-a number

The MDZ-number [88] [100] describes the effects of track geometry on a railway vehicle depending on the line speed. Within the figure, differences in longitudinal level, alignment and cross level are combined to one value. By means of the exponential number 0.65, the influence of line speed is reduced, which should reflect the effect of spring elements. The factor *c* makes it possible to adapt the MDZ-a number to the characteristics of different railway networks.

$$\mathrm{MDZ} = c * \frac{1}{L} * V^{0,65} * \sum_{i=1}^{\frac{L}{\Delta x}} \sqrt{(\Delta v')^2 + (\Delta h + \Delta \ddot{u})^2} \tag{5}$$

c	factor for the adaption to different railway networks
L	segment length
V	line speed
Δx	distance between two measuring points
$\Delta v'$	vertical deviation
Δh	horizontal deviation
$\Delta \ddot{u}$	deviation in cross level

Federal Railroad Administration TQI

The Federal Railroad Administration (FRA) [101] uses a geometry index based on space curves to describe track quality. Therefore, the actual space curve L_i for a geometry parameter *i* is calculated based on the measuring data. In a second step, the length of the space curve is referred to the theoretical base length of the considered segment L_0.

$$L_i = \sum_{j=1}^{n-1} \sqrt{\left(x_{i(j+1)} - x_{ij}\right)^2 + \left(y_{j+1} - y_j\right)^2} \tag{6}$$

$$\mathrm{TQI_i} = \left(\frac{\mathrm{L_i}}{\mathrm{L_0}} - 1\right) * 10^6 \tag{7}$$

i	track geometry parameter
L_i	length of the measured space curve
L_0	theoretical basic length (segment length)
x_j	measured value at point j
y_j	kilometre at point j

Overall Track Quality Index OTGI

The overall track quality index (OTGI) [102] considers mean values and standard deviations of the different track quality parameters. The parameters are weighted with line-class specific factors. Within the index, track gauge is considered separately for track extension and gauge narrowing, as their limit values differ significantly. The formula of OTGI is:

$$\mathrm{OTGI} = \frac{\frac{a}{2} * \mathrm{GI}^+ + \frac{a'}{2} * \mathrm{GI}^- + b * \mathrm{AI} + c * \mathrm{PI} + d * \mathrm{TI}}{\frac{a + a'}{2} + b + c + d} \tag{8}$$

The different sub-indices are calculated as follows:

$$\mathrm{GI}^+ = \left|\bar{x}_{\mathrm{Gauge}} + 3 * \mathrm{SD}_{\mathrm{Gauge}}\right| \tag{9}$$

$$\mathrm{GI}^- = \left|\bar{x}_{\mathrm{Gauge}} - 3 * \mathrm{SD}_{\mathrm{Gauge}}\right| \tag{10}$$

$$\mathrm{AI} = \left(\left|\bar{x}_{\mathrm{Alignment\ Left}}\right| + 3 * \mathrm{SD}_{\mathrm{Alignment\ Left}} + \left|\bar{x}_{\mathrm{Alignment\ Right}}\right| + 3 * \mathrm{SD}_{\mathrm{Alignment\ Right}}\right)/2 \tag{11}$$

$$\mathrm{PI} = \left(\left|\bar{x}_{\mathrm{Profile\ Left}}\right| + 3 * \mathrm{SD}_{\mathrm{Profile\ Left}} + \left|\bar{x}_{\mathrm{Profile\ Right}}\right| + 3 * \mathrm{SD}_{\mathrm{Profile\ Right}}\right)/2 \tag{12}$$

$$\mathrm{TI} = \left|\bar{x}_{\mathrm{Twist}}\right| + 3 * \mathrm{SD}_{\mathrm{Twist}} \tag{13}$$

a, a', b, c, d	weighting-factors
GI^+	gauge index (extension)
GI^-	gauge index (narrowing)
TI	twist index
PI	longitudinal level index
AI	alignment index
$\bar{x}$	mean value
σ	standard deviation

By analysing different TQIs, it becomes evident that, in some aspects, they show similarities and, in other aspects, quite significant differences. Hence, the quality indices provide various advantages and disadvantages for assessing track geometry.

Nevertheless, the different indices exhibit properties that impede a reliable evaluation of track quality in total:

- Many TQIs do not consider all relevant track quality parameters.
- Many formulas are structured in such a way that it is not possible to extend them by further track quality parameters.
- In many cases, weighting/calibration factors or specific limit values are necessary. These factors often depend on country- or line-specific properties or are completely incomprehensible. This makes it difficult to calculate reproducible results and to apply the TQI to other networks.
- Often, conventional standard deviations are used within the formulas. This brings the disadvantage of distorted results in curves and especially transition curves as the signals of track gauge, twist and cross level show much higher values there.
- In most quality indices the results of different track quality parameters are cumulated or a mean value is calculated. This brings the disadvantage that some parameters are over-represented as their raw signal scatters in a higher amplitude range (e.g. longitudinal level) compared to other parameters (e.g. twist).

TUG_TQI

To counteract the above-mentioned shortcomings of existing approaches, a new TQI is developed that is called TUG_TQI [96]. The calculation of the TUG_TQI is based on the TQI of Federal Railroad Administration and develops it further. To calculate the TQI for one signal, the length of the space curve of the signal L_i is referred to the theoretical base length of the considered segment L_0. Higher amplitudes in the signal and therefore a higher number of failures result in a greater length of the space curve and therefore a higher (worse) value of the TQI. To avoid that some parameters are over- or under-represented, all the considered signals are normalised in a first step. This is done by dividing the measured values through their limit values. Hence, the TQI is not calculated with signal amplitudes but based on utilisation rates. This allows for the combination of different signals without any weighting process. Due to this procedure, also the line speed is considered implicitly as it contributes to the determination of limit values. Special attention has to be paid to the signal of track gauge as its positive and negative tolerances are quite different. Hence, this signal is separated along the zero line and the positive and negative parts are normalised to the respective limit values.

The space curve lengths of the normalised measuring signals L_i are calculated by means of the following formula:

$$L_i = \sum_{j=1}^{n-1} \sqrt{\left(x_{(j+1)} - x_j\right)^2 + \left(y_{i(j+1)} - y_{ij}\right)^2} \tag{14}$$

i	track geometry parameter
L_i	length of the measured space curve
x_j	kilometre at point j
y_j	utilisation rate at point j

Based on the space curve length, the formula below makes it possible to calculate the TQI for every measuring signal separately. The factor of 10^8 has the task to scale the result to a value range that is easily interpretable.

$$TQI_i = \left(\frac{L_i}{L_0} - 1\right) * 10^8 \tag{15}$$

i	track geometry parameter
L_i	length of the measured space curve
L_0	theoretical basic length (segment length)

For the final TUG_TQI, the mean value of all contained sub-indices is calculated:

$$TUG\_TQI = \frac{\sum_{i=1}^{n} TQI_i}{n} \tag{16}$$

TQI_i	sub-index for every considered track geometry parameter
n	number of considered track geometry parameters

Compared to already existing TQIs, the TUG_TQI comes with the following advantages:

- The mathematical model can be applied for every measuring signal in every railway network.
- Within the TQI, it is possible to consider every desired measuring signal.
- The methodology considers peak values as well as the scattering of the signal.
- Widening of track gauge in curves and desired twist in transition curves do not lead to oversubscriptions in the results.
- Gauge narrowing is considered separately.
- Due to the normalisation of the signal based on their limit values, line speed is considered implicitly.

The TUG_TQI comes along with many advantages compared to existing approaches. Nevertheless, it has to be stated that also the TUG_TQI is intended to describe track quality in an overall way. Consequently, this means TQIs should not be used for maintenance planning, as they combine different parameters and therefore do not provide enough detail information to schedule a specific task.

5.5 Standard deviation

As TQIs are not suitable for planning specific maintenance tasks, in Europe, the standard deviation of vertical track geometry is an established parameter for making maintenance decisions regarding tamping [75] [80] [103]. Therefore, the further focus is set on this track quality parameter.

The standard deviation shows the deviation of the signal in relation to the mean value of the signal over all measured values of the observed section:

$$SD = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \bar{x})^2}{N-1}} \qquad (17)$$

x_i	measured value at point i
$\bar{x}$	mean value of all measured values within the considered section
N	number of measuring points within the considered section

The present research shows that it is possible to use different types of standard deviations of the longitudinal level for describing track quality. By calculating standard deviations, it is important to decide on the influence length. Furthermore, it must be considered whether the standard deviation is computed discreetly for fixed sections or continuously by means of a sliding window over the analysed track section.

Figure 26 shows the longitudinal track level (continuous signal in the background) as well as three different types of standard deviations for a track section of 1.2 km as an example. The dotted blue line represents the moving standard deviation for 100 m. The continuous red line depicts the standard deviation calculated for fixed sections of 200 m. The dashed green line shows the modified standard deviation used in Austria (σ_{mod}) [104]. The last-mentioned track quality figure is not a standard deviation in a mathematical sense. For calculating such a modified standard deviation, the mean value of the longitudinal level of left $x_{le,i}$ and right rail $x_{re,i}$ is determined as a first step. Subsequently, an average track geometry deviation for each cross section is calculated.

This represents the mean value of all distances *N* from the zero line to the measured values in a sliding section with a length of 100 m. In a last step, this average deviation is multiplied by 1.35 making the quality figure comparable with a conventional standard deviation of 100 m. The modified standard deviation can be expressed by the following formula:

$$\sigma_{\text{mod}} = \frac{\sum_{i=1}^{N} \left| \frac{x_{le,i} + x_{ri,i}}{2} \right|}{N} * 1.35 \tag{18}$$

$x_{le,i}$	measured value of longitudinal level (left rail) at point i
$x_{ri,i}$	measured value of longitudinal level (right rail) at point i
N	number of measuring points within the considered section

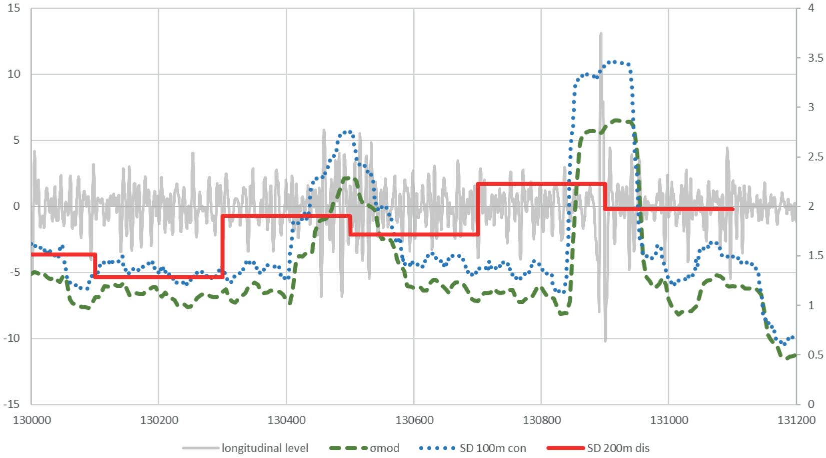


Figure 26: Different methods for describing track quality in the longitudinal level context.

All of the above-mentioned standard deviations have advantages and shortcomings when using them as a quality index. Fixed sections are used for example by Famurewa et al. [75], Caetano et al. [76] or Vale et al. [78]. The major advantage of a standard deviation of 200 m in fixed track sections is the very easy handling, as only one value must be calculated and interpreted for 200 m. Memory capacity as well as the computing effort are relatively low in this case. Furthermore, for making maintenance decisions, section lengths are partially already predefined as fixed 200 m sections. A moving average standard deviation provides the major advantage that track quality problems are only pointed out within the chosen influence length. Figure 26 shows that for the single failure at km 130.900. The standard deviation for fixed 200 m sections leads to 400 m of comparatively poor track quality due to the single failure. This occurs because the single failure is at the border of two sections and thus influences them both.

In contrast to this, the continuous standard deviation for 100 m shows poor track quality only in a section of 100 m, which is the influence length. The advantage of this is that maintenance tasks can be planned wherever they are necessary. It is important not to choose an influence length that is too short, as this would make it possible to detect single failures, but would hinder the detection of coherent poor track quality sections.

As depicted in Figure 26, the modified standard deviation shows a very similar characteristic to that of the conventional standard deviation for 100 m. The main difference is the reduced influence of single failures. This is a relevant advantage for a quality figure that should describe the general track quality of a section and not only the influence of one single failure on the whole section.

Another shortcoming of standard deviations for fixed sections is the calculation of time series. This can be explained by means of the example in Figure 27. This picture shows the same track section as Figure 26 after spot tamping at the single failure at km 130.900. The continuous line in the background shows the current longitudinal level (after spot tamping) and the dashed blue line the longitudinal level before spot tamping. The light red continuous line represents the standard deviation for fixed 200 m sections before spot tamping and the dark red continuous line after spot tamping. This means both the standard deviation and thus the track quality, improves significantly over 400 m, although, tamping was carried out only on a length of 30 m for removing the single failure. By calculating time series at km 130.800 for example, it appears that the track quality has improved significantly. Since no maintenance action was carried out there, however, analysing time series in this cross section would lead to incorrect conclusions.

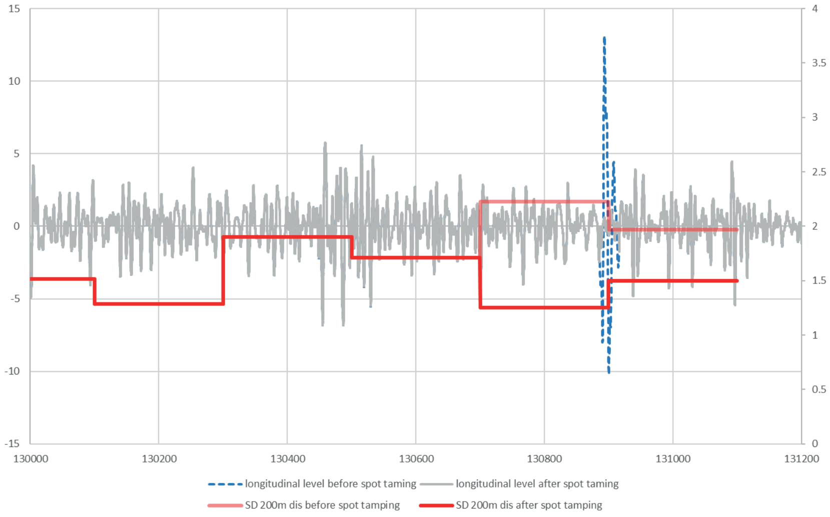


Figure 27: Track quality regarding longitudinal level after spot tamping.

To summarise the findings of the present chapter, the chosen influence length should not be too long. High influence lengths would shuffle different independent effects over the considered area and may lead to tamping interventions where they are not necessary.

Too short influence lengths tend to depict single failures being eliminated by spot tamping machinery which is not in the scope of this thesis. An influence length of 100 m is detailed enough without losing the connection to continuous maintenance lengths. Furthermore, the calculation of the standard deviation should be done continuously by means of a sliding window to get reliable results for time series analyses.

5.6 TQI for tamping scheduling

In Austria, the modified standard deviation of the longitudinal level with an influence length of 100 m (chapter 5.5) is established for making maintenance decisions regarding tamping. Although this quality figure is widespread for planning line tamping tasks, it contains one shortcoming: all the other track quality parameters described in chapter 5.2 are not directly considered. However, it turned out that it is clearly sufficient to consider standard deviation of longitudinal level for the predictive planning of line tamping tasks. The main reasons are described below.

The track geometry analyses by Hansmann [66] could show that there is a one-sided correlation between failures in alignment and longitudinal level. This means that a failure in alignment also causes a deflection in vertical direction. Vice versa, however, this correlation does not apply. Consequently, by analysing the data, a failure in horizontal direction can also be recognised in the signal of longitudinal level.

Another parameter that is always linked to track geometry is track gauge. However, for planning tamping tasks it is not reasonable to consider this signal, as it is normally not possible to remove failures in track gauge by means of tamping actions. Thus, regarding track gauge for tamping scheduling might lead to wrong conclusions.

A further factor that is often seen as critical is twist. Twist is a three-dimensional track quality parameter, which means that it contains vertical track geometry as well. Hence, it can be assumed that failures in twist are also visible in the signal of longitudinal level and its standard deviation. To verify this assumption, an evaluation is conducted that compares values of twist and σ_{mod}. Therefore, 40 measurement runs from the Austrian rail network between 2008 and 2016 are randomly selected. In the next step, areas are identified for all the measuring runs separately, where poor values for the twist signal (base 16 m) occur. For the definition of a poor value, 90 % of the alert limit (2.8 mm/m for speeds up to 160 km/h) are chosen which equals 2.52 mm/m. Afterwards, for these areas, an average value for σ_{mod} is calculated and compared to the average σ_{mod} of the whole measurement run. The detailed results of the evaluation are shown in Table 25 (Annex) and reveal that almost in every case σ_{mod} is much higher for sections with poor twist values than on average. By calculating an average σ_{mod} for all measurement runs, the result is a value of 0.975 mm. Compared to that, in areas with poor twist values, σ_{mod} is 1.845 mm on average (Figure 28). Furthermore, the examination shows that poor twist values can only be observed in 0.4 % of all analysed sections. These results clearly show that poor twist values also lead to significant higher values of σ_{mod}. This result would be even clearer if instead of 90 % of AL a higher value (e.g. IL) would be used to define poor twist values.

Hence, the assumption that relevant information for planning line tamping tasks provided by the twist signal is already covered by σ_{mod}, can be confirmed.

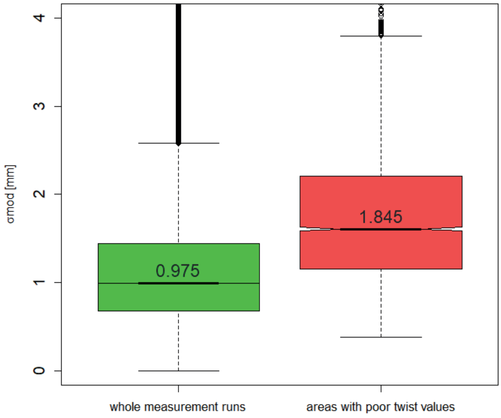


Figure 28: Comparison of σ_{mod}-values for whole measurement runs and in areas with poor twist values.

Cross level is also a quality parameter that is dealing with the vertical geometry of the track. Hence, failures within this signal must also be visible within the standard deviation of vertical track geometry.

It has to be stated that the facts described above are true for using σ_{mod} to schedule line tamping tasks in advance. This does not substitute checking the signals of all track quality parameters with regard to exceedances of IL or IAL in single spots, which is important to guarantee safe railway operation. Though, this is another topic because, in the case of exceedances of these limits, an immediate intervention is necessary and there is no space to optimise any scheduling. However, within a sustainable maintenance regime, immediate interventions should not play a big role, as isolated defects are already fixed within planned maintenance tasks before they reach any IL or IAL.

According to the ÖBB RW 06.01.01 [105], also for σ_{mod}, an intervention (4.0 mm) and an immediate action limit (4.8 mm) exist. These values are exceptionally high and rarely occur in a well-maintained network like in Austria. Furthermore, before reaching these values, in most cases a limit value of the raw signal of longitudinal level is exceeded long before, which would describe a reactive maintenance regime again. Because of this, additional alert levels for the purpose of maintenance planning are determined that depend on both line speed and track age. The higher the line speed, the stricter the requirements on track quality are. Furthermore, as the intervention level depends on track age, a younger track should be maintained earlier than a track at the end of its service life.

Therefore, for every line speed, a lower limit for younger tracks and an upper limit for older tracks is established [104]. It must be stated that these levels were developed as recommendations for maintenance planning. Hence, they do not describe any safety critical condition and are not mandatory. The two intervention levels can be determined by the following formulas:

$$ILE_{young\_track} = 1.5 * \left(\frac{100}{V_{max}}\right)^{0.65} \tag{19}$$

$$ILE_{old\_track} = 2 * \left(\frac{100}{V_{max}}\right)^{0.65} \tag{20}$$

ILE	intervention level
V_{max}	maximum line speed

In the course of one investigation, tamping tasks on a railway line in Austria regarding the exceedance of the two thresholds are analysed. The selected railway line has a length of about 250 km and the tamping actions took place between 2001 and 2015. Hence, about 1,500 tamping tasks can be analysed. The results show that in 94 % of all tamping sections, the lower intervention threshold is reached. The upper threshold is exceeded in 84 % of all analysed sections. Thus, Austrian Federal Railways follow their own rules for maintenance planning based on modified standard deviation of longitudinal level. The analyses are also carried out separately for straight tracks and curves, but no significant differences can be observed. The relatively high percentages show that σ_{mod} is very well suited for planning and predicting tamping tasks.

Based on the information and findings in this chapter, the modified standard deviation of vertical track geometry with an influence length of 100 m is used for all further considerations relating to the planning of tamping actions.

6

Track quality behaviour over time

Based on σ_{mod}, it is possible to describe track quality in a reliable way in order to derive tamping tasks. However, as the goal of the present thesis is to plan tamping actions automatically for the upcoming years in a sustainable way, knowing about the current track quality condition is not yet enough. Rather it is necessary to use accurate prediction models for estimating the point in time when an intervention level will be reached in the future. An appropriate prediction model has several main requirements:

- It has to describe the quality behaviour over time, which means that the fitting of the mathematical curve to the real behaviour must be as good as possible.
- The prediction accuracy should be high - this should also be true in cases when few measuring data are available.
- It should be able to deal with maintenance tasks, as these measures improve the quality level and thus impact the regression function abruptly.
- The model should be simple enough to allow a huge amount of data to be dealt with adequately. For a medium-sized network of 4,400 km and up to 20 years of historic data, there are over 350 million measurement values available which have to be analysed.

This chapter deals with the topic of predicting the next tamping intervention based on time series analyses [106]. Therefore, different prediction models are examined and compared. Furthermore, an algorithm is introduced that automatically calculates time series and enables the analysis of track quality behaviour over time.

6.1 Deterioration models

The most important precondition for analysing track quality over time is to know the characteristic of the deterioration process. This characteristic makes it possible to describe the past behaviour and predicting it in the future. For this, it is theoretically possible to use any existing regression function. In practice, linear [87] [107], multi-linear [108], logarithmic [109] and exponential [75] [110] functions are used for predicting track quality at a specific time $Q(t)$ by means of the initial quality Q_N, the deterioration rate b and time t (Figure 29).

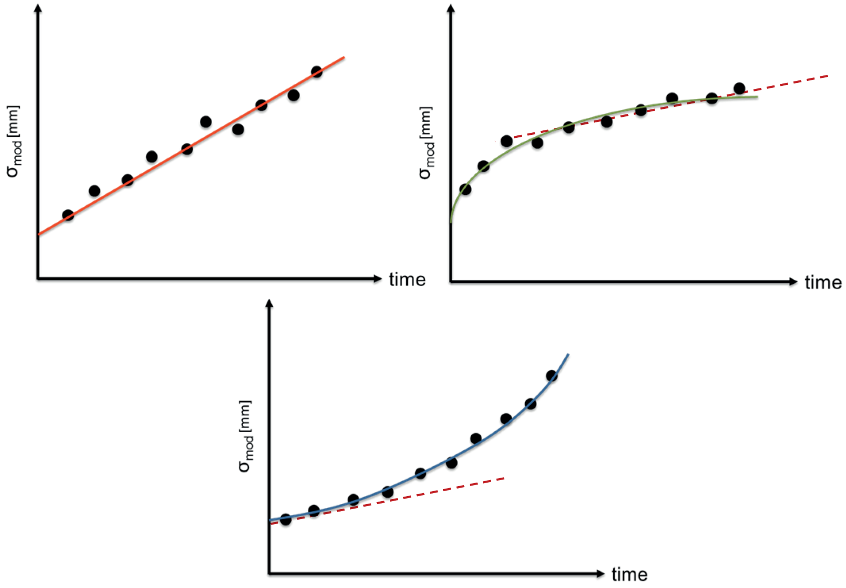


Figure 29: Possible behaviour of σ_{mod} over time: linear (above left), logarithmic (above right), exponential (below).

All of these functions exist in reality, depending on the track (ballast) condition [111]. Logarithmic functions fit for the behaviour directly after renewal or tamping (initial settlements) and for very old, stiff ballast beds. Initial settlements describe a short-term effect directly after a maintenance task, where no measuring data from the recording car are available. Thus, it is not intended to depict these initial settlements by means of a separate regression function directly after tamping. Nonetheless, initial settlements are considered indirectly through the results of the regression, as a high value for the initial quality Q_N means high initial settlements. In case of very poor ballast quality and especially in the event of executing tamping measures at a very late stage, deterioration rates can be very high. In these cases, exponential curves can be applied. Alternatively, these situations can be described by means of two linear regression functions, the first one with a lower and the second one with a higher slope [108]. Because of high speeds as well as high demands on track quality and riding comfort in the Austrian network, these cases are nearly not covered within the considered data set. The linear regression somehow makes its appearance in-between these processes. The advantage of one single linear regression function between two tamping tasks is the mathematical simplicity and stability.

Furthermore, it is easily comprehensible for track engineers who have to derive actions based on the regression results. Figure 30 shows the three deterioration functions within a hypothetical service life of a railway track.

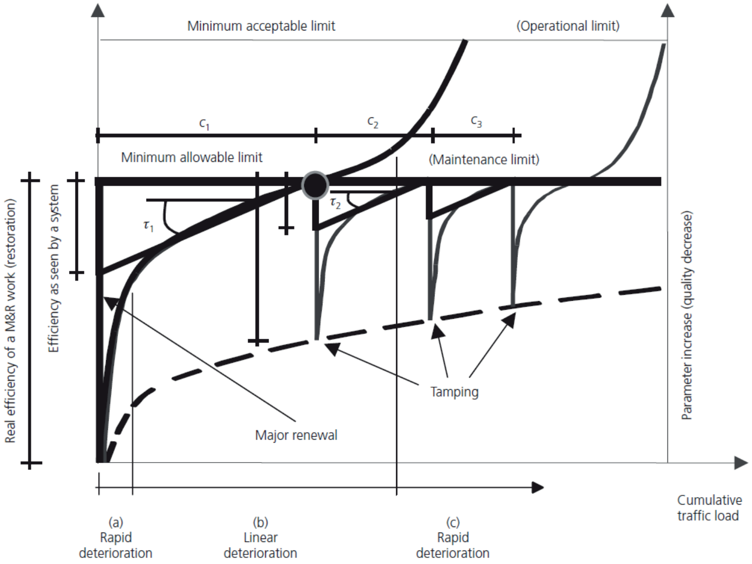


Figure 30: Hypothetical track geometry deterioration over service life [111].

The considered functions for the further analyses are of the forms:

$$Q(t) = Q_N + b * t \tag{21}$$

$$Q(t) = b * \ln(t) + Q_N \tag{22}$$

$$Q(t) = Q_N * e^{b*t} \tag{23}$$

Q(t)	predicted track quality at time *t*
Q_N	initial track quality
b	deterioration rate
t	time

To find the most suitable model for describing track quality behaviour using one regression function for all tracks in the network, the R^2 of measuring data between two tamping tasks are compared for the three regression functions. The coefficient of determination R^2 is the coefficient of explained variation and total variation [112]. This relation can be expressed by the following formula:

$$R^2 = \frac{\sum_{i=1}^{n} (\hat{y}_i - \bar{y})^2}{\sum_{i=1}^{n} (y_i - \bar{y})^2} = 1 - \frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{\sum_{i=1}^{n} (y_i - \bar{y})^2} \tag{24}$$

$\hat{y}_i$	point on the regression line
$\bar{y}$	mean value
y_i	measuring point

The same railway line is chosen for the comparison of the three functions, as described in chapter 5.6. Hence, about 123,000 time periods between two tamping tasks are available for the examination. In the following, the time span between two tamping tasks is called deterioration period.

Table 2 shows the results of the analyses regarding the fitting of the three regression functions to the real behaviour. Thereby, the medians of the different function types are depicted in total and clustered by track age.

Table 2: Medians of R^2 of different regression functions clustered regarding track age and in total.

	0-15 years	16-30 years	>30 years	total
linear	0.962231	0.961606	0.964854	0.961702
logarithmic	0.921099	0.927251	0.931595	0.921107
exponential	0.934836	0.936367	0.940934	0.935075

By analysing the medians of R^2, it can be shown that the linear regression function offers the highest value (0.96) and therefore shows the best fitting to the real behaviour. With a R^2 of 0.94, the exponential function shows the second-best value.

The logarithmic function shows a value of 0.92. This means that all function types show relatively high values, although the linear function shows the best match. Furthermore, it can be stated that no significant influence of the track age on the match of the different regression functions is found. This does not affect the fact that the longitudinal level (raw signal) and thus “track quality” behaves over-linearly (exponentially). Physics indicates that with an increasing failure the input forces increases as well and thus accelerate the failure growth. This is proven by raw signal analyses of single failures in longitudinal level. However, linear regression function is best suited for analysing track quality behaviour described by standard deviation of longitudinal level, over time and for tracks of all ages. This result is consistent with earlier studies, which showed a linear track quality behaviour between two tamping tasks during the economic service life of the track [103] [111].

6.2 Prediction accuracy

For creating an appropriate prediction model, not only the fitting of the regression function to the actual behaviour is of great importance, but also the prognosis capability. For checking this, 123,000 cross sections of the above-mentioned line are examined with respect to their behaviour at several points in time. Initially, the first two measuring points of a deterioration period are thus taken, and a linear regression is calculated until the real end of the period. This linear regression provides a predicted end quality before tamping (Figure 31, Q_{reg2}) based on the calculation with two measuring points. Subsequently, this calculated quality level before tamping can be compared with the real end quality level that is based on the regression function with all measuring points of the period (Figure 31, continuous line and Q_{ult}). Matching the predicted and the real end quality makes it possible to determine the deviation of the prediction model compared to the real behaviour (Figure 31, Δ_{reg2}). By computing the deviations for all available deterioration periods, it is possible to calculate the statistical distribution (Figure 31, right part) and statistical key figures such as the median. After calculating the regression and doing the comparison with two measuring points, the process is repeated with three measuring points, and so forth. In Figure 31, this methodology is depicted for the regression by means of two, three and four measuring points for the linear function as an example. The more measuring points that are included in the regression, the lower the deviation from the real quality should be (Figure 31, Δ_{reg}) and, as a result, the prediction accuracy should be improved.

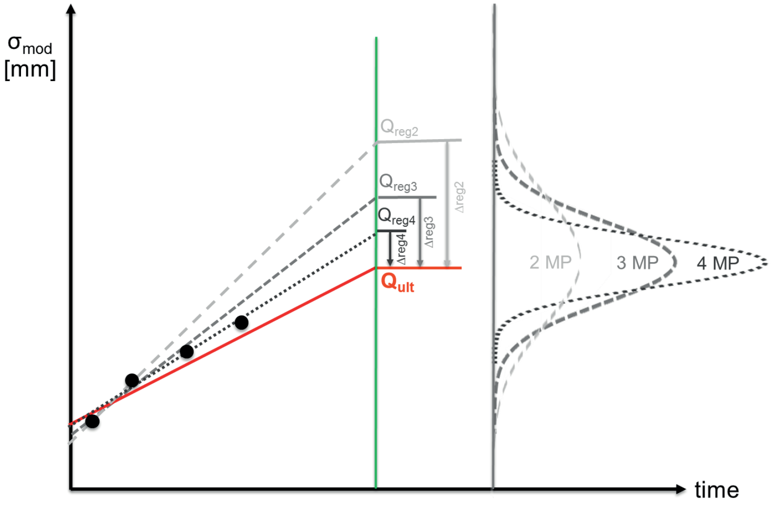


Figure 31: Comparison of predicted (with two, three and four measuring points (MP), based on a linear regression function as an example) and real track quality behaviour.

In the present study, this analysis is executed for the linear, the logarithmic and the exponential function to prove their prediction effectiveness. It must be stated that using the difference between the predicted end quality (Figure 31, Q_{reg}) and the real end quality (Figure 31, Q_{ult}) is not entirely correct, as the real end quality already depends on the analysed function type. To counter this, a comparison between the last measuring point and the predicted quality level based on the analysed regression function is also made. This method comes with the advantage that the last measuring point is always the same and thus independent of the function type. However, this approach has the disadvantage that a computed value from a prediction function is compared with a single measured value that may not necessarily represent the real end quality. By carrying out these investigations, it turns out that there is no significant difference in the characteristic of the results. Thus, for the further examinations, only the deviations between the predicted and the real end quality are considered.

Figure 32 shows the results of the analysis regarding the prediction accuracy. The bars represent the medians of the deviation between the predicted and the real end quality of all analysed deterioration periods for the three function types. Furthermore, the number of analysed deterioration periods is shown in the lower bars.

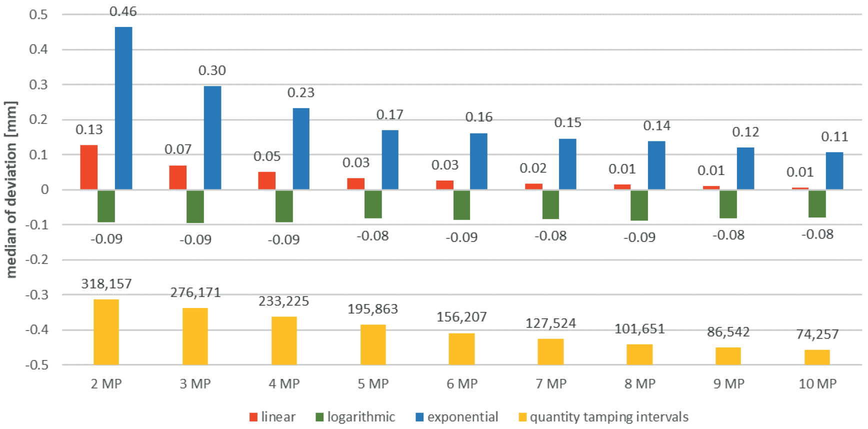


Figure 32: Deviations of predicted and real end quality before tamping for linear, logarithmic and exponential regression function and quantity of analysed tamping intervals for different amounts of measuring points (MP).

The bars in Figure 33 display the interquartile ranges of the deviations of the three function types. Hence, by means of this figure, the scattering of the deviations can be analysed.

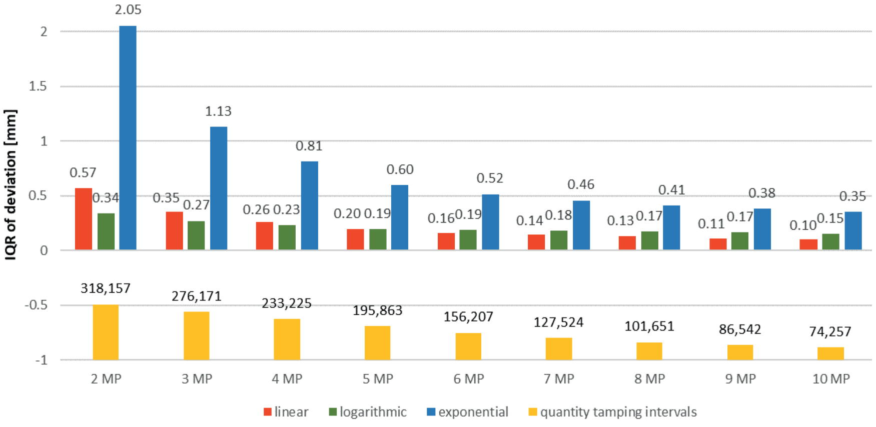


Figure 33: Interquartile range (IQR) of deviations of predicted and real end quality before tamping for linear, logarithmic and exponential regression function and quantity of analysed tamping intervals for different amounts of measuring points (MP).

Figure 32 shows that the median of the deviation between the predicted and real end quality offers the smallest values for the linear regression function. The deviation of the logarithmic function is slightly smaller for two measuring points, but as soon as three measuring points are available, the linear function shows the best predictability. In summary it can be stated that the exponential regression function clearly has the highest deviations, independent of the number of existing measuring points. The results of the linear function show that a higher number of measuring points leads to a significant improvement in prediction quality, especially between two and four measuring points. If four measuring points are available, the deviation is statistically nearly 0. Similar results were found by Caetano et al. [76], although in this study the horizon of prediction only reached the next measuring run and not the end of the deterioration period. The logarithmic regression function shows a comparatively good accuracy when having a small amount of measuring points, but it is nearly not possible to improve the prediction accuracy by increasing the amount of available measuring points. In contrast to the linear and the exponential functions, the logarithmic function shows negative deviations. This means that the predicted end quality before tamping is better than the real quality. The positive deviations of the linear and the exponential functions lead to worse predicted qualities compared to the real qualities, which means a more cautious approach. By examining the scattering of the deviations in Figure 33, it turns out that the exponential function shows the highest scattering and for this the highest uncertainties. Up to five measuring points, the lowest scattering is shown for the logarithmic and from six measuring points for the linear function. In general, all three functions show a decreasing scattering by an increasing amount of measuring points.

To sum up all the interpretations, the logarithmic function shows a comparatively high standard of accuracy when only a low quantity of measuring points is available. The logarithmic function has the disadvantage that it underestimates the end quality in any case. This can result in planning tamping tasks too late and thus to a poor track quality that cannot be restored appropriately anymore. Ultimately, this can cause a significant reduction in service life [113]. Because of the mathematical characteristic of the exponential function, significantly higher end qualities are predicted than are seen in reality. The consequence for planning tamping tasks is that they will be scheduled much too early. This is not reasonable from an economic perspective and can also lead to a reduction in service life, as tamping also contributes to ballast deterioration [3].

It must be borne in mind that the investigations and comparisons that are carried out base on existing data and deterioration periods and therefore might not include all possible effects.

Thus, the developed algorithm and model is valid for tracks that are maintained on a relatively high level. Tracks with very poor quality could not be integrated into the examinations since inadequate measuring data between two tamping tasks in these sections is available for computing reliable regression functions. Furthermore, the data quality is often relatively poor in these areas.

In summary, it can be stated that the linear regression function is best suited for describing and predicting track quality behaviour over time. The linear function displays the best fitting of the real measuring points compared to the two other regression function types (exponential and logarithmic). Furthermore, the linear function shows the lowest deviations between the real and the predicted end quality when there are three or more measuring points. If fewer than three points are available, a serious prediction should not be attempted in any case, because the influence of an outlier can be much too high. As the analysed railway line consists of different radii down to 189 m, varying maximum speed, tracks of different age, superstructure types and substructure conditions as well as changing axle load collectives, the results are correct for all influencing parameters of track geometry. Thus, the linear regression function is used for further considerations, analyses and models.

6.3 Creation of time series

The assessment of track quality for condition-based maintenance planning requires time series analyses over long periods. As a precondition for this, all relevant data must be stored in a data warehouse in an appropriate way. Therefore, the TUG database is introduced which forms the base for all data analyses executed for this thesis.

Afterwards, the challenges of track quality examinations over long time spans are described and an algorithm for a deterioration model is presented that allows for sophisticated time series analyses.

6.3.1 TUG database

A necessary precondition for any measurement data analysis is a well-structured data warehouse. This is especially true for computing and analysing time series of data. In order to obtain this, the Institute of Railway Engineering and Transport Economy at Graz University of Technology established a data warehouse [114] in cooperation with Austrian Federal Railways in 2003.

The data warehouse currently contains track information on 4,400 track kilometres of Austria's main network. Within the data warehouse, the network is divided into equidistant cross-sections every five meters, whereby the measurement data is linked with asset information (Figure 34), although the raw signal of various measurements is available every 25 cm.

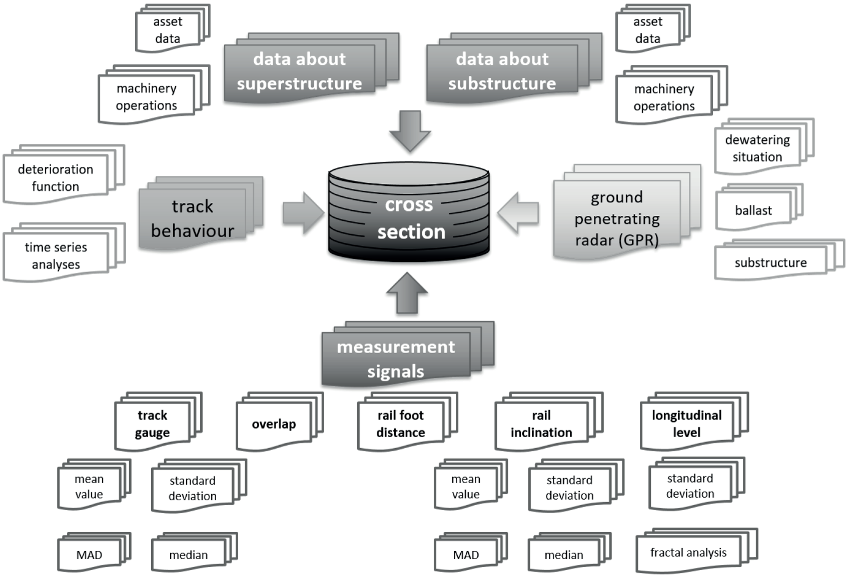


Figure 34: Data warehouse of the Institute of Railway Engineering and Transport Economy at Graz University of Technology.

The database content is grouped into information regarding three main points. First, it contains general asset information such as age and type of sleepers and rails, traffic volume, speed limits, radii, bridges, tunnels, crossings, stations and any executed and recorded machinery action. Second, the data base contains data from the track recording vehicle and further information processed from this data. Thereby, it links raw measurement data such as track gauge, overlap, rail foot distance, rail inclination and track geometry to every cross section and the asset information. The measurement data history goes back to the early 1990s but was interrupted by a changing of the track recording car in the early 2000s, with the result that the data warehouse provides measurement signals only from 2001 until now. On this base, specific algorithms are applied to calculate values that allow for a component specific condition evaluation (chapter 11) for every cross-section and measurement run.

Furthermore, time series analyses are computed to describe track behaviour and quality over time. The third available data source is evaluations executed with the ground penetrating radar (GPR) [115] describing track quality with respect to the dewatering situation, ballast and substructure condition.

By combining and connecting all this information, the precondition is given for analyses of time series and condition-based maintenance planning, both in accordance with the track components and characteristics.

6.3.2 Algorithm for computing time series automatically

The simple application of regression functions to the data may be not sufficient for the calculation and correct interpretation of time series over longer periods and for entire railway networks. Since tamping tasks improve track quality, the data should be split into deterioration periods that are, as a rule, automatically bounded by tamping (or ballast cleaning/renewal) tasks at the beginning and at the end. Furthermore, the influence of outliers has to be eliminated. For this, a sophisticated algorithm was developed for handling the required measuring data and maintenance actions over time [106] [116] [117].

The developed algorithm is based on the modified standard deviation of the longitudinal level (σ_{mod}), as this quality parameter is considered for planning tamping tasks (chapter 5.6). To describe a track's quality and behaviour over time, it is necessary to carry out regression analyses between two tamping tasks. For this purpose, one approach is to use the executed and registered tamping actions, which are stored in the data warehouse described in chapter 6.3.1 and to calculate several regression curves between two maintenance actions. The results should be deterioration rates b, the initial quality Q_N and the quality level at the end of the deterioration period shortly before intervention Q_{ult} for any specific deterioration period n.

Such a deterioration period together with the related values is displayed in Figure 35 as an example. The y-axis shows the track quality in the form of σ_{mod} and the measurement date is depicted on the x-axis. Increasing values of σ_{mod} means a deterioration of track quality has occurred and that a certain limit will be exceeded if no maintenance is done. A low deterioration rate of track quality means that intervention levels are reached later and therefore the deterioration periods are longer. This means the longer the periods, the better a track's geometry and the less maintenance needs to be carried out. Hence, care must be taken with the initial quality when building a new track, which is one of the most important parameters for track assessment and track quality behaviour over time [113].

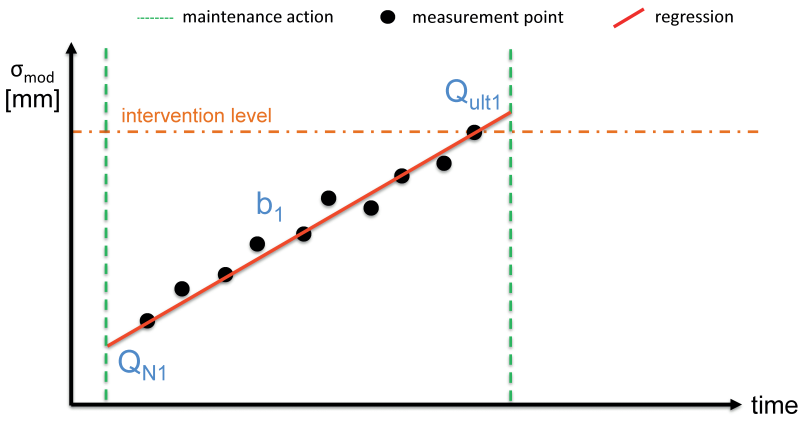


Figure 35: Results of a regression analyses for one deterioration period.

Generally, by taking into account longer time series, considerably more than one deterioration period occurs within one cross section. This makes time series analyses quite challenging as described in the following. Figure 36 displays an exemplary plot of a cross section with 18 measurements. As shown, after the first 5 measurements, track quality improves significantly. Also, after 8, 11 and 14 measurements, significant improvements are evident, suggesting a tamping action.

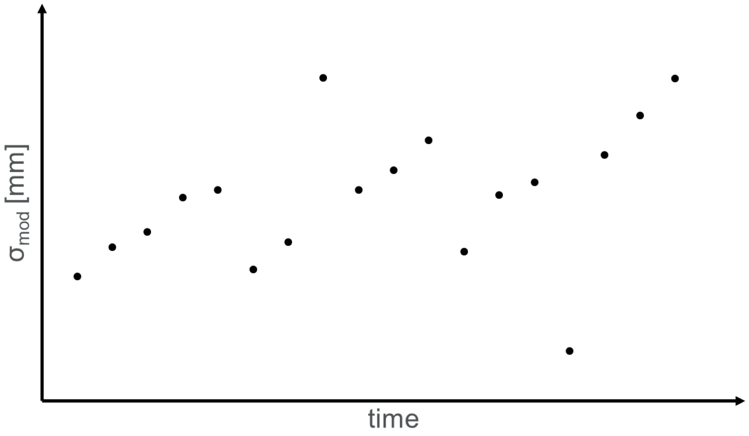


Figure 36: Modified standard deviation of the longitudinal level (σ_{mod}) of a cross section over time.

Since not all the maintenance work carried out is well documented, however, an additional approach is necessary. Thus, an algorithm is developed in order to find the improved track geometry and therefore executed, but not documented tamping actions. First, the difference between the following and the previous measurement is calculated for all available values within a cross section. If the track deteriorates, the following value of the standard deviation of vertical track geometry is higher than the previous one and therefore the difference between these values is positive. Conversely, this means that a lower following value is an indication for an improved track quality and therefore an executed maintenance action.

However, when evaluating track measuring data over time, taking care of data quality is especially important. The simple consideration of any data without any deeper investigation may lead to completely wrong conclusions, as the following example should illustrate: as shown in Figure 37, the algorithm calculates five deterioration rates for the analysed cross section. The second and last one are steeper than the other three, which means that the track deteriorates rapidly, and the standard deviation of vertical track geometry will exceed the admissible limit. By studying the measurement points more closely, it becomes clearly visible that two measurements are likely to be outliers (Figure 37, measurement point 8 and 15 in red) leading to false deterioration periods and rates. An interpretation of these results would therefore result in an incorrect understanding and assessment of track quality behaviour over time.

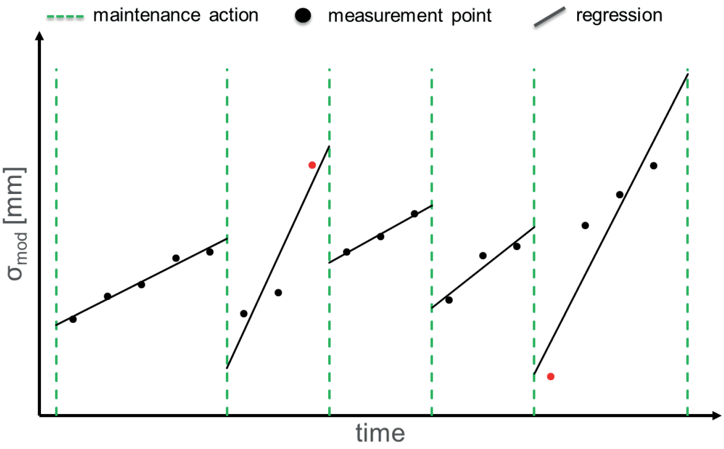


Figure 37: Regression analysis with five deterioration periods.

To avoid such mistakes, the evolved algorithm is expanded to detect outliers and delete them. Recent research has shown that the mean absolute deviation (MAD) is more robust against outliers than the mean when dealing with multivariate data [118]. However, the analyses show that it is not entirely reasonable to use the MAD itself as this is not sensitive enough to detect outliers and tamping tasks in a best way. Therefore, the MAD is multiplied with a calibration factor of 0.79 which is developed within a simulation. The aim of this simulation is to detect as many actually executed tamping actions as possible with the developed algorithm. For this examination, a line with a length of about 200 km is chosen, where the executed tamping actions are well recorded and documented. Within the analyses, the algorithm is executed eight times with varying multiplication factors for the MAD. The following factors are used: 0.3, 0.5, 0.7, 1.0, 2.0, 3.0, 5.0, 8.0. After each simulation, the amount of calculated tamping tasks is compared with the actually executed ones and the deviation is expressed in per cent. As the results in Figure 38 show, for multipliers from 0.3 to 0.7, more tamping tasks are calculated than executed in reality and for multipliers from 1.0 and higher, fewer tamping tasks are found than actually carried out.

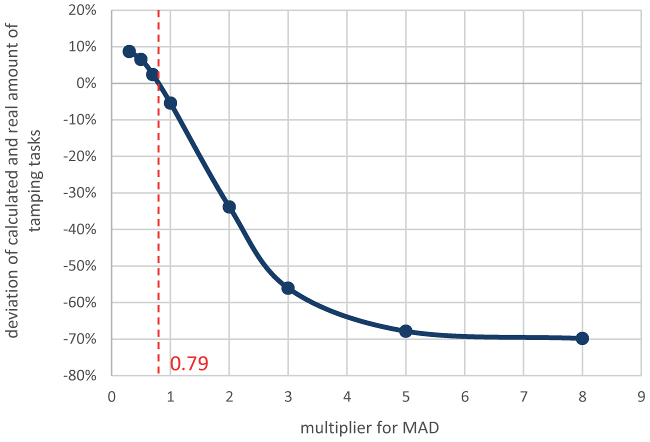


Figure 38: Deviation of calculated and real number of tamping tasks based on varying multipliers for MAD.

By connecting the points in the diagram and intersecting the line with the 0-level, it turns out that the best match of computed and real tamping tasks is obtained with a factor of 0.79.

The process of outlier detection is based on a straightforward principle. For every measurement, the algorithm analyses the difference between the previous and the following measurement. For example, in Figure 37, the algorithm computes the difference between the measurements 7 and 8 as well as 8 and 9. If both computed differences exceed the value of the previously computed MAD multiplied by 0.79 and one calculated value is negative, the measurement is considered as an outlier and has to be deleted. As shown in Figure 37, the algorithm identifies two outliers (measurements 8 and 15) and deletes it for the further considerations.

In the next step and without the already deleted outliers, deterioration rates are calculated again, which is displayed in Figure 39. Therefore, the same principle (by means of the new calculated MAD, multiplied by 0.79) is used as described before. The comparison of Figure 37 and Figure 39 impressively points out the effort involved in outlier detection and the approach with the MAD. The new calculation results in three instead of five deterioration periods. It shows deterioration rates that are much more consistent and can be used for analysing track quality behaviour over time.

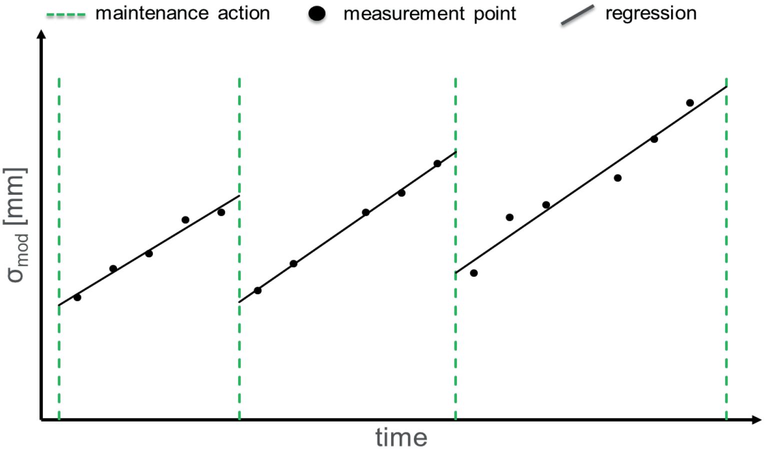


Figure 39: Detection and elimination of outliers and computing of regression analyses.

The last step within the algorithm is the replacement of the detected tamping actions with those which have been executed in reality. This means that the information of the cross section is linked with asset data and if a tamping action near the detected one was executed, the algorithm replaces the detected one and uses the real one instead. Furthermore, this shows, that the approach is based on both scientific analysis and real data.

The entire developed algorithm is now able to divide measuring data of long time series into reasonable deterioration periods. It is possible to describe the quality behaviour by means of key figures like the initial quality after tamping, the end quality before the next tamping task and the deterioration rate. The results are stored in the TUG database and can be used for any examination in the context of track quality. Hence, the algorithm and its results form the basis for predicting track quality over time with reliable data.

7

Track quality behaviour after tamping

At the current stage, it is possible to describe track quality behaviour over time. Furthermore, the linear regression model makes it possible to calculate the point in time at which the related intervention level is reached. Also, the statistical evidence can be determined for this. For maintenance scheduling, this means that it is possible to predict the point in time at which the next tamping task will be necessary. The question that then arises from this is: What happens after a tamping intervention? It is crucial to answer this question because of the following two reasons:

- Within a considered track section, areas of both good and poor track quality exist. This leads to quite different behaviour over time in these areas and therefore to different points in time at which the intervention level is reached. Hence, in some sections, tamping has to be executed earlier and more often than in others. The goal of the present thesis is to predict all tamping actions for the upcoming years and not only the next task, as this may lead to a significant underestimation of interventions in some sections. Therefore, it is of great importance to know about the quality behaviour after a tamping task to be able to also plan the subsequent measure(s).
- One goal of the present thesis is to find an optimal intervention level for tamping. This can only be reached by comparing different cases and strategies. Therefore, it is necessary to know about the quality behaviour after tamping to estimate the consequences of the intervention at a specific quality level.

7.1 Basics

As explained in chapter 6.3.2, track quality deteriorates over time until an intervention level is reached, and tamping is executed. The whole process within one deterioration period *n* can be described by means of the initial quality Q_{N1}, the deterioration rate b_1 and the end quality Q_{ult1}. Generally, after the tamping task, the track quality improves significantly to a new initial quality level Q_{N2}. Afterwards, the degradation process starts again with a new deterioration rate b_2. These processes are graphically illustrated in Figure 40. This means, by using a linear deterioration model, the relevant parameters after the tamping process are the initial quality and the new deterioration rate. By means of these two values, it is possible to describe the whole behaviour in the next deterioration period and to determine the point in time when the intervention level is reached again.

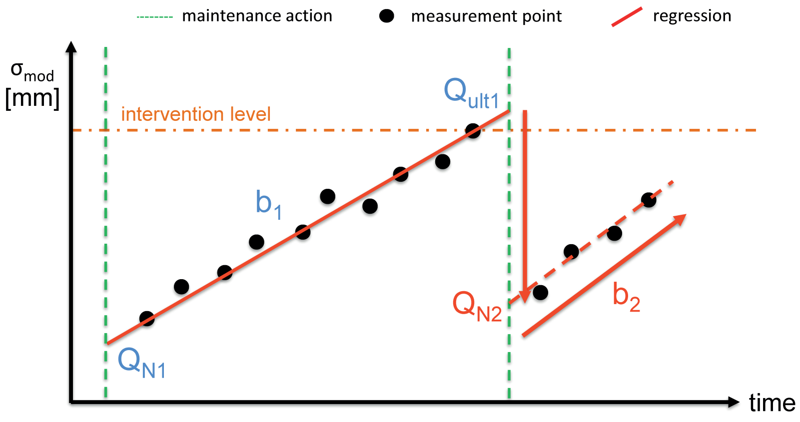


Figure 40: Deterioration process of track quality and behaviour after tamping.

In literature, several approaches exist for modelling the improvement in track quality after a tamping intervention. The developed approaches are called restoration models [119]. Most of the research in this area is based on an ORE report from 1988 [120], which shows that track quality after a tamping task depends on the quality level before the intervention. Based on this value, the restoration of track geometry is modelled with a linear function in many investigations, and the required regression parameters are determined [75] [76] [77] [79] [121]. Other examinations use probabilistic models by dealing with the topic of restoration of track quality after tamping. Audley et al. [103] use a two parameter Weibull distribution to model the probability for reaching a specific quality level after tamping. Furthermore, they show that, besides the quality level before tamping, line speed and maintenance history can influence the result.

Quiroga et al. [84] simulate track geometry degradation by using Monte Carlo Simulation. The study shows that with an increasing number of tamping interventions, the variances of initial track quality after tamping and degradation rates are increasing.

The review of existing approaches shows that most of the already existing restoration models used are highly simplified. Most of them just use a linear regression model and the only input parameter is the track quality before the intervention. The development of the deterioration rate after executing tamping is not considered in most instances, although this is a crucial value. As railway tracks show quite different properties over the network, it can be assumed that also the restoration process varies strongly under different circumstances. These boundary conditions include track quality parameters like initial quality and degradation rate in the deterioration period before the intervention. Furthermore, infrastructure properties like track age or type of superstructure might influence the behaviour. In the reviewed studies these factors are often neglected, as only one single restoration model exists or only few of them are considered.

Hence, for the present investigations it is necessary to execute detailed evaluations of the restoration process for different boundary conditions. The procedure and the results are presented in the next sub-chapters.

7.2 Track quality parameters after tamping

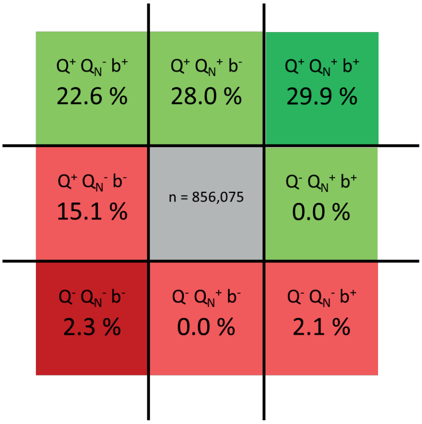
As a first step, the changes of relevant track quality parameters due to a tamping action are analysed in a general way all over the network. Therefore, for all cross sections within the TUG database, consecutive deterioration periods are determined that are confined by tamping tasks. As a result, 856,075 combinations of deterioration periods fulfil the requirements and can be analysed. For the examination, the changes in absolute track quality (Q: Q_{N2} compared to Q_{ult1}), in deterioration rates (b: b_2 compared to b_1) and in initial quality (Q_N: Q_{N2} compared to Q_{N1}) are determined. The results are listed in Table 3 and show that, in nearly 95 % of the cases, tamping effects an absolute improvement in track quality. This means that the intervention fulfils its intended task of restoring track geometry. In the remaining 5 % of the cases, no improvement of track quality can be recognised due to the tamping task – there is even a deterioration. This might happen in the event of poorly executed interventions or at the end of the service life when the ballast bed shows a high degree of pollution, and tamping is not an appropriate measure anymore. Furthermore, the results in Table 3 show that the deterioration rate b and the initial quality Q_N improve in just over 50 % of cases from one deterioration period to the next.

Table 3: Change of track quality parameters after tamping.

	improvement absolute	deterioration absolute	improvement relative	deterioration relative
change in Q	818,408	37,667	95.6 %	4.4 %
change in Q_N	495,667	360,408	57.9 %	42.1 %
change in b	467,417	388 658	54.6 %	45.4 %

The high amount of improvements in track quality parameters may look unusual at first sight as rather a deterioration of track quality with increasing service life would be expected. Though, one has to consider that the results in Table 3 are based on analyses that are carried out for each track quality parameter separately. However, in reality both initial quality and deterioration rate are responsible for track quality behaviour and therefore have to be considered together. Thus, their improvements and deteriorations from one period to the next have to be analysed in a combination (together with the absolute change in track quality). The results of this analysis are shown in Figure 41. The "+" means an improvement, and the "-" a deterioration of the related parameter from one deterioration period to the next.

As the absolute track quality only deteriorates after tamping in very few cases, describing more or less tracks at the end of their service life, these instances are not the focus of the present investigations. In contrast, the changes in Q_N and b are of great interest. The results show that, in about 17 % of all cases, both parameters are worse compared to the deterioration period before tamping. In about 25 % of cases, the initial quality; and in 28 %, the deterioration rate takes poorer values after the intervention than before. This means that, in about 53 % of the examined settings, one of the relevant parameters deteriorates after tamping. In about 30 % of the analysed situations, the initial quality and also the deterioration rate show improved values after executing a tamping action.



$Q^+ Q_N^- b^+$ 22.6 %	$Q^+ Q_N^+ b^-$ 28.0 %	$Q^+ Q_N^+ b^+$ 29.9 %
$Q^+ Q_N^- b^-$ 15.1 %	n = 856,075	$Q^- Q_N^+ b^+$ 0.0 %
$Q^- Q_N^- b^-$ 2.3 %	$Q^- Q_N^+ b^-$ 0.0 %	$Q^- Q_N^- b^+$ 2.1 %

Figure 41: Change of track quality parameters after tamping in dependence of other parameters.

Similar analyses regarding the change of track quality parameters after a tamping task were already executed by Hummitzsch [27] and Holzfeind [122]. Within these studies the MDZ-a number is used for describing track quality, and an exponential function is used for depicting track behaviour over time. Although the analyses are executed with a much lower number of samples, similar to the present study, the results show quite diverse characteristics. Deteriorations of one parameter are also noticeable as the deterioration of both and the improvement of the two values.

Another investigation on the change of track quality parameters after tamping is done by Hansmann [123]. Likewise, in this examination MDZ-a number is used together with an exponential deterioration model. The results are shown in Figure 42. Similar to the present analyses, the results show that, in only 18 % of all cases, both track quality parameters (initial quality and deterioration rate) deteriorate from one period to the next one. In most cases, one of the parameters improves, and one deteriorates due to the tamping task. In 17 % of cases, both of the parameters improve.

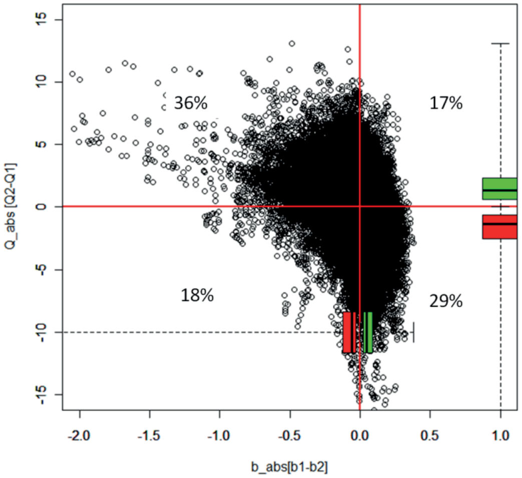


Figure 42: Change of track quality parameters after tamping in dependence of parameters before the measure, regarding [123].

To summarise, the results regarding the change of track quality parameters due to a tamping task show quite varying values and therefore no clear result. This is also true for former studies using other track quality parameters and deterioration models. Thus, it can be concluded that the restoration process of track geometry after tamping is not a trivial one and must depend on further parameters as well.

7.3 Dependencies of track quality parameters after tamping

Because of the unclear result in the last chapter, it is now the goal to investigate different possible dependencies of the quality parameters. Therefore, potential dependencies on track age, other quality parameters and type of superstructure are examined. The upcoming analyses should be valid for typical situations under the given boundary conditions. To meet this requirement, only combinations of deterioration periods are considered, where the R^2 of both regressions before and after the tamping task take values of 0.9 and higher. This should avoid the considerations of outliers and untypical situations that are not representative. Furthermore, the presented analyses are executed for tracks equipped with concrete sleepers, as this is currently the main sleeper type in the Austrian core network. In the end, the results are compared with other sleeper types. After filtering the data based on the described boundary conditions, 252,439 pairs of deterioration periods all over the network are available for the further analyses.

Before the analyses are presented, an approach is introduced to calculate the cumulated traffic load over the service life, which is an important precondition. Furthermore, a methodology is explained to test a possible correlation between the different parameters.

7.3.1 Model for accumulated traffic load

It is assumed that track age might be one important factor influencing the restoration process of track geometry after a tamping intervention. Therefore, it is necessary to define what exactly is meant by track age. In the simplest case, track age means the service life of the track in years. However, in an inhomogeneous network like in Austria, this interpretation might lead to a bias in the results. The reason for this is the strongly varying traffic load on different lines, which effects track performance much more than the temporal component. This means, instead of the track age in years, it is more reasonable to use the accumulated load of the track up to a specific point for describing a “track’s age”.

A challenging issue is that many tracks in the network already exhibit quite long service lives. For these long time spans, there is no detailed information about the development of traffic loads available. Therefore, in many cases, it is not possible to calculate exact accumulated traffic loads until a specific point in time.

To face this challenge, Hansmann [66] developed a model that makes it possible to calculate accumulated traffic loads as accurately as possible at least on the basis of an estimation. The basis for the model is the information about traffic loads in specific years. These traffic loads are available from the TUG database for every cross section in the network. However, as these traffic loads are only known for some few years, that is not yet enough information to calculate the accumulated traffic load for the whole service life. Therefore, the general development of traffic loads over time has to be known. Figure 43 depicts the development of traffic loads over the years in the form of gross ton kilometres globally over the network.

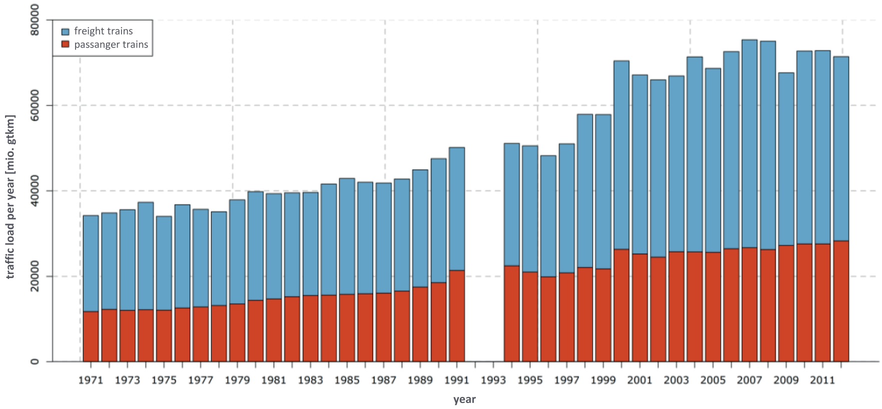


Figure 43: Network-wide development of gross ton kilometres between 1971 and 2012 [66].

The growth of traffic load over time can best be approximated with a quadratic regression function of the form:

$$y(x) = C_1 * x^2 + C_2 * x + C_3 \tag{25}$$

Now, on the one hand, cross section specific traffic load information is available that can be used as a reference point. On the other hand, a network-wide trend of the increase of traffic load over the years is known. By now combining these information, it is possible to determine the accumulated traffic load for every cross section in the network to any specific point in time. Therefore, the following formula is used:

$$\overline{b_n} = b_0 * \frac{\overline{B_n}}{\overline{B_0}} \tag{26}$$

$\overline{B_n}$	global load value given by the regression for year n
$\overline{B_0}$	global load value given by the regression for the reference year
b_0	section-specific load value drawn from the cross-section
$\overline{b_n}$	calculated load value for the cross-section

This methodology is utilised for all further analyses dealing with the behaviour of track geometry parameters over the service life.

7.3.2 Correlation analyses for two parameters

To check the relation between two parameters, correlation analyses are executed. As only metric variables are analysed for the present purposes, it would be theoretically possible to use different methodologies to test a possible correlation [124].

The Spearman’s rank correlation provides the advantage that also non-linear relationships can be detected, and normally distributed input data are not a precondition. As non-linear correlations might appear, and the data sets are not normally distributed, this method is chosen for all the following correlation analyses. The Spearman´s rank correlation determines how well an arbitrary monotonic function describes the relationship between two variables. Spearman´s correlation coefficient ρ_{SP} (Spearman’s rho) is formed by converting the data to ranks prior to the calculation as follows [125]:

$$\rho_{SP} = \frac{\sum_i (rg(x_i) - \overline{rg}_x)\big(rg(y_i) - \overline{rg}_y\big)}{\sqrt{\sum_i (rg(x_i) - \overline{rg}_x)^2 \sum_i \big(rg(y_i) - \overline{rg}_y\big)^2}} = \frac{Cov\big(rg_x, rg_y\big)}{\sigma_{rg_x}\sigma_{rg_x}} \qquad (27)$$

$rg(x_i)$	rank of x_i (the same is true for y_i)
$\overline{rg}_x$	means of the ranks of x (the same is true for y)
σ_{rg_x}	section-specific load value drawn from the cross-section
$Cov\big(rg_x, rg_y\big)$	covariance of rg(x) and rg(y)

The Spearman’s correlation coefficient takes values from -1 to 1 and is interpreted as follows:

$\rho_{SP} > 0$	Concordant monotonic relationship, Trend: x large → y large; x small → y small
$\rho_{SP} < 0$	Inverse monotonic relationship, Trend: x large → y small; x small → y large
$\rho_{SP} \approx 0$	Non-monotonic relationship

The minimum value for a statistically significant correlation strongly depends on the scaling of the input data and especially their population. To assess whether a calculated coefficient indicates a statistical correlation or not, the probability value (p-value) is used. The p-value estimates the probability of the occurrence of the null hypothesis. The null hypothesis describes the case of independence or, in other words, a non-correlation.

As described above, the level of significance highly depends on the number of observations. For observations of more than 30 values, the t-distribution requires a value *t* above 2.3263 to confirm a significant correlation with a probability of at least 99 %:

$$t = \left|\left(\frac{\rho_{SP}}{\sqrt{1-\rho_{SP}^2}} \times \sqrt{n-2}\right)\right| > 2{,}3263 \qquad (28)$$

By means of the formula, the critical correlation coefficient ρ_{SP} can be calculated for any amount of observations n [59]. The lower the observation quantity, the higher the required value is for ρ_{SP} to detect statistically significant correlation. For example, an amount of 100,000 observations requires a ρ_{SP} value of 0.0074 to describe statistically significant correlation. As the present examinations include a much higher amount of observations, correlation is proven by exceeding a ρ_{SP} value of 0.0074 in any case.

At this stage, all preconditions are given for investigating the relations between the different track quality parameters before and after a tamping task.

7.3.3 Influence of service life

At first, the different track quality parameters are investigated in relation to the service life. As already mentioned, service life is expressed by the cumulated traffic load. Figure 44 shows the development of Q_{ult} – which equals the intervention level for tamping – over the life span of the track. The results indicate that the intervention level increases significantly until 200 million gt. After this point is reached, Q_{ult} stays more or less stable until about 450 million gt.

This result fits quite well to the strategy of a compliant intervention threshold where newer tracks are maintained earlier than tracks at a later stage of the service life [104] [113]. The results for tracks with very high cumulated loads seem to contradict the strategy, as they exhibit lower intervention levels again. However, these high cumulated traffic loads are only reached on important lines with high loads and speeds (in contrast to lower cumulated traffic loads where all types of lines are mixed up). As these lines have higher requirements on track quality, the tracks are maintained at a lower intervention threshold.

By executing the correlation analysis as explained in chapter 7.3.2, the value for ρ_{SP} results in 0.0531. This value seems to be quite low, but as already mentioned, for checking the minimum value for a statistically significant correlation the p-value must be calculated. As the p-value is calculated to $2.2*10^{-16}$ in the present case, the null hypothesis is to be discarded, and correlation is present.

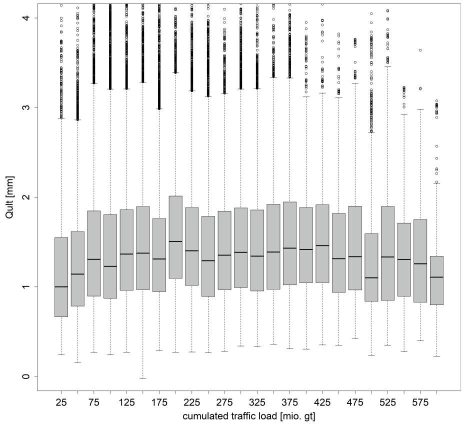


Figure 44: Development of Q_{ult} over cumulated traffic load.

Besides the intervention level, the development of the initial quality Q_N and the deterioration rate b are also analysed over the service life. The left picture in Figure 45 shows that the value for Q_N is increasing with an increasing cumulated traffic load. This means the initial quality is decreasing over service life on average. The trend is particularly apparent up until about 425 million gt. At higher cumulated loads, the scattering in the results is quite high. By executing a correlation analysis, a correlation coefficient of 0.1132 with a corresponding p-value of $2.2*10^{-16}$ can be indicated. This means a statistically significant correlation is proven. In the right picture of Figure 45, the deterioration rates are depicted in dependence of the cumulated traffic loads. The picture does not show a clear relation. Until about 475 million gt, the degradation rates stay more or less on a stable level. At higher cumulated traffic loads, the deterioration rate is even lower.

A reason for this might be an already polluted and therefore very stiff ballast bed, where track geometry deterioration only occurs to a small extent. The correlation analysis provides a ρ_{SP} of 0.0085 with a p-value of $1.836*10^{-5}$. Despite the unclear trend in Figure 45 and the low ρ_{SP}-value, correlation is proven with statistical evidence.

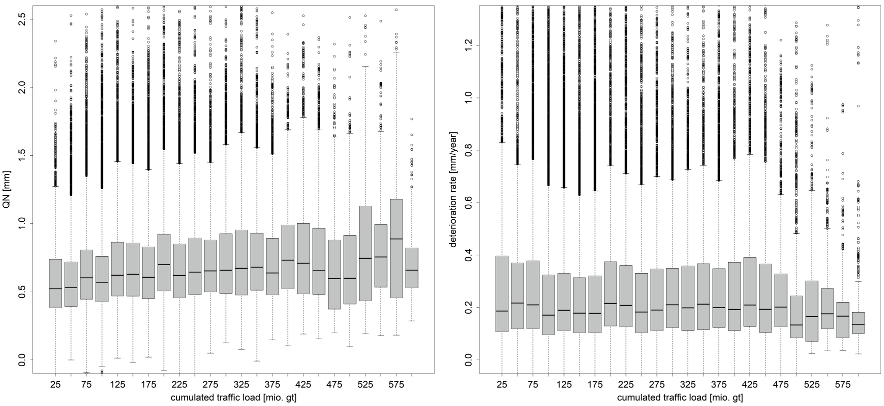


Figure 45: Development of Q_N (left) and b (right) over cumulated traffic load.

7.3.4 Influence of intervention level Q_{ult1}

In a subsequent step, the influence of the intervention level Q_{ult1} on the relevant quality parameters in the next deterioration period is investigated (Figure 46).

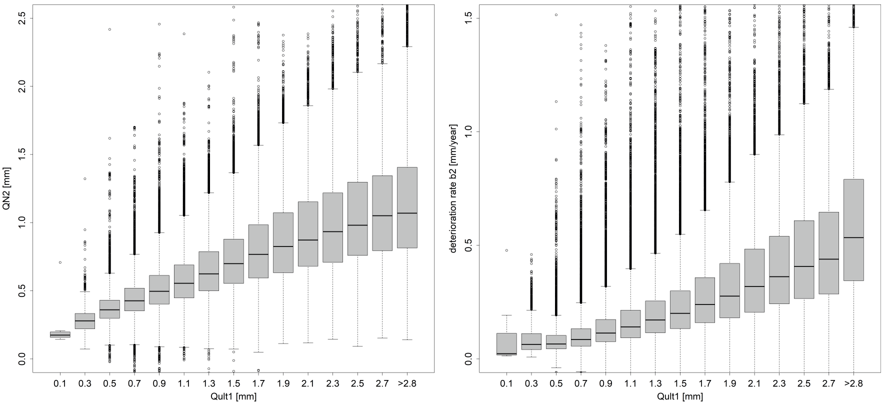


Figure 46: Development of Q_{N2} (left) and b_2 (right) in dependency of intervention level Q_{ult1}.

The left graphic in Figure 46 shows that the initial quality of the next deterioration period increases sub linearly with an increasing intervention level. By executing the correlation analysis, a correlation coefficient of 0.6535 results with a p-value of $2.2*10^{-16}$.

By taking a look on the right picture in Figure 46, it becomes evident that the deterioration rate after a tamping intervention increases over linearly with the intervention level. The correlation analysis provides as a result a ρ_{SP} value of 0.6423 (p-value: $2.2*10^{-16}$). The results show that both the initial quality and also the deterioration rate after a tamping action demonstrate statistically significant correlation with the intervention level.

7.3.5 Influence of deterioration rate b_1

It is assumed that, in addition to the intervention level, the deterioration rate before a tamping task also influences the track quality parameter after the measure. These possible dependencies are tested, and the results are shown graphically in Figure 47.

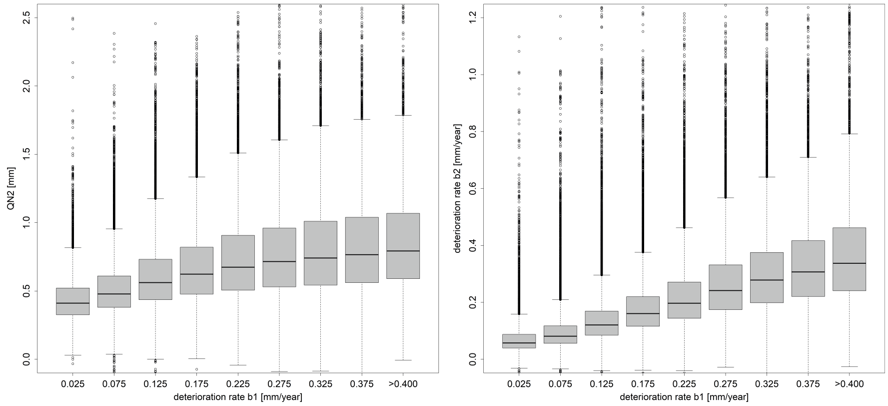


Figure 47: Development of Q_{N2} (left) and b_2 (right) in dependency of deterioration rate b_1.

The left picture demonstrates that the new initial quality after an intervention is worse in the case of high deterioration rates before maintenance. Generally, this trend has a sub linear characteristic. By checking the relation with the correlation test, a ρ_{SP} value of 0.4377 is computed with a corresponding p-value of $2.2*10^{-16}$. The right picture in Figure 47 displays that the deterioration rate after a tamping intervention increases quite linearly with the deterioration rate before the measure. The correlation analysis provides a correlation coefficient of 0.7566 with a p-value of $2.2*10^{-16}$. In summary, the results indicate that both the initial quality as well as the deterioration rate after tamping have statistically significant correlation with the deterioration rate before the tamping measure.

7.3.6 Influence of initial quality Q_{N1}

After considering the above-mentioned dependencies between the track quality parameters, initial cluster analyses are executed. Although the characteristics of the results showed reasonable trends, the absolute values did not seem to be meaningful. Thus, it is evident that there must be another parameter influencing the track quality parameters after a tamping intervention and the clustering needs further refinement. For this purpose, the initial quality in the deterioration period before the intervention is investigated, which was neglected at first. The left picture in Figure 48 shows the relation between the initial quality in the first and the second deterioration period. For exceptionally good initial qualities, the results indicate a very sharp deterioration in the next period. However, it must be stated that these cases occur quite rarely. Apart from these special observations, the initial quality in the next deterioration period decreases with a decreasing initial quality in the period before. The development is more or less linear, although the trend flattens out slightly for poorer initial qualities. The correlation analysis provides a correlation coefficient of 0.6008 with a corresponding p-value of $2.2*10^{-16}$. The right picture in Figure 48 demonstrates the relation between the initial quality in the first and the deterioration rate in the second deterioration period. In this case, the same behaviour can be observed as before: exceptionally high initial qualities in the first period lead to comparatively poor values for the deterioration rate. Besides these special situations, an increase of the deterioration rate is noticeable with a decreasing initial quality. The trend is more or less linear. The performance of the correlation analysis provides a ρ_{SP} value of 0.3578 and a p-value of $2.2*10^{-16}$. Based on the results, it can be stated that the initial quality in the first deterioration period shows statistically significant correlation with the initial quality and also the deterioration rate in the following period.

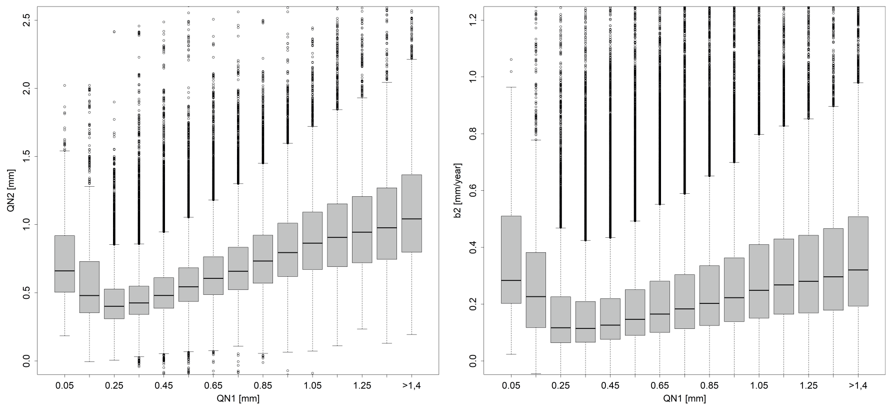


Figure 48: Development of Q_{N2} (left) and b_2 (right) in dependency of initial quality Q_{N1}.

7.3.7 Summary of correlation analyses

In Table 4 and Table 5, the results of the correlation analyses are summarised. Table 4 shows the dependencies of the cumulated traffic load with the relevant track quality parameters. Table 5 demonstrates the relations between the track quality parameters within the deterioration period before and after a tamping task. The first line in every cell contains the correlation coefficient ρ_{SP} and the second line the corresponding p-value.

Table 4: Results for the correlation analyses of cumulated traffic load and track quality parameters (first line: correlation coefficient ρ_{SP}, second line: p-value).

	Q_N	b	Q_{ult}
cum. load	0.1132 $2.2*10^{-16}$	0.0085 $1.836*10^{-5}$	0.0531 $2.2*10^{-16}$

Table 5: Results for the correlation analyses of track quality parameters in two consecutive deterioration periods (first line: correlation coefficient ρ_{SP}, second line: p-value).

	Q_{N2}	b_2
Q_{ult1}	0.6535 $2.2*10^{-16}$	0.6423 $2.2*10^{-16}$
b_1	0.4377 $2.2*10^{-16}$	0.7566 $2.2*10^{-16}$
Q_{N1}	0.6008 $2.2*10^{-16}$	0.3578 $2.2*10^{-16}$

As mentioned before, the significance of the correlation coefficient depends on the number of observations. For example, for 100,000 observations, a coefficient of at least 0.0074 is required to prove significant correlation. In the present examinations, the number of observations lies above 200,000, and the lowest value for ρ_{SP} is 0.0085. Thus, it can be stated that statistically significant correlation can be found in any of the analysed cases. Due to the fact that every pair of parameters is tested with the same amount of observations, the corresponding correlation factors can be directly compared. In general, the lowest correlations occur between the cumulated traffic load and the track quality parameters. In particular, the relation between the cumulated traffic load and the deterioration rate is the lowest. The highest correlation can be found between the deterioration rates before and after the tamping task. In total, the highest correlations are observed between the intervention level and the quality parameters after the maintenance action.

7.4 Model for estimating track quality after tamping

The results of the analyses in chapter 7.3 show that there are many dependencies between different (track quality) parameters. The expression of all these dependencies through mathematical formulas would lead to unclear models with too much complexity.

It must be remembered: The goal of the present thesis is to develop a model that can be used for maintenance planning based on real data with an acceptable computing effort and is comprehensible for track engineers.

To fulfil these requirements on the one hand and depict all the occurring relations on the other, the results are clustered based on the findings of the correlation analyses. For the clustering, the following four parameters are considered, which turned out to be relevant for the track quality parameters after a tamping task:

- Intervention level Q_{ult1}
- Deterioration rate b_1
- Track age in the form of cumulated traffic load
- Initial quality Q_{N1}

The results in chapter 7.3 show that the intervention level and the deterioration rate before the measure show the highest correlation with the track quality parameters after the task. Hence, these two characteristic values are chosen as main criteria for clustering. Thereby, the intervention level is divided into groups with a bandwidth of 0.2 mm.

This means the first group contains intervention levels from 0 mm to 0.2 mm, the second from 0.2 mm to 0.4 mm and so on. In this way, 15 groups are formed until the value of 3.0 mm is reached. Any cases that exceed an intervention level of 3.0 mm are summarised in an own additional group. The deterioration rates are split into segments with a range of 0.05 mm/year. This results in seven groups until a value of 0.35 mm/year. Cases where this value is passed are categorised in their own additional group. The bandwidth of the groups is determined by means of sensitivity analyses. Within these analyses, the changes in the results and especially their information value (excessively rough segmentation leads to a loss of information; excessively fine subdivision leads to a high number of segments without any additional benefit) are tested by varying the bandwidth. The segmentation results in a matrix with 16 columns for the intervention level and eight lines for the deterioration rate. Therefore, the matrix already contains 128 different cases based on the subdivision with only two parameters.

As the goal is to create a manageable model in the end, a rougher segmentation is chosen for the parameters with lower correlations. For the track age in the form of cumulated traffic loads three classes are defined. The first group contains young tracks that have undergone traffic loads up to 225 million gt. Within this group, slightly higher initial qualities and deterioration rates are noticeable. For tracks that exhibit between 225 million gt and 475 million gt, no clear trend or difference is recognisable regarding the track quality parameters. This range forms the second group of segmentation.

Above 475 million gt, slightly lower initial qualities and deterioration rates are identifiable and therefore make up the third group. For the segmentation of initial qualities, a subdivision in three groups is also carried out. As the results in chapter 7.3.6 do not show any logical thresholds for segmentation, initial qualities are subdivided in three equal-sized groups. The first group includes the best 33 % of the values up to an initial quality of 0.54 mm. The second group incorporates values from 0.54 mm up to 0.83 mm, and the third group contains the worst 33 % with values above 0.83 mm.

Based on the executed segmentation, 16 different groups for the intervention level and eight groups for the deterioration rate, each with three groups for the cumulated load and the initial quality are the results. In total, this gives amounts to 1,152 cases that have to be considered. In practice, not all of these theoretical combinations occur, as some of them are not realistic. This concerns especially extreme manifestations of the different values in different directions. For example, no cases for young track exist where the initial quality and the deterioration rate are very low and a tamping task is executed only at a very high intervention level. For any further consideration, the results are clustered in nine tables.

Each table contains one combination of different situations regarding cumulated traffic load and initial quality. Within one table, the clustering concerning the intervention level and the deterioration rate is visible. Table 6 shows exemplarily the resulting table for cumulated traffic loads under 225 million gt and an initial quality between 0.54 mm and 0.83 mm.

Table 6: Results (absolute) for traffic loads < 225 million gt; Q_{N1} 0.54 mm – 0.83 mm.

		Qult1																
		0 - 0.2	0.2 - 0.4	0.4 - 0.6	0.6 - 0.8	0.8 - 1.0	1.0 - 1.2	1.2 - 1.4	1.4 - 1.6	1.6 - 1.8	1.8 - 2.0	2.0 - 2.2	2.2 - 2.4	2.4 - 2.6	2.6 - 2.8	2.8 - 3.0	> 3.0	
b1	0 - 0.05			0.5472	0.5819	0.6676	0.6885	0.7546										QN1
				0.3878	0.4446	0.4907	0.5384	0.5599										QN2
				0.0326	0.0391	0.0411	0.0447	0.0460										b1
				0.0402	0.0535	0.0614	0.0749	0.0870										b2
				0.5906	0.7223	0.8832	1.0725	1.2383										Qult1
		0	0	50	763	816	286	39	0	0	0	0	0	0	0	0	0	n
	0.05 - 0.1			0.5394	0.5808	0.6495	0.6794	0.6846	0.7311	0.7568	0.7345							QN1
				0.3899	0.4466	0.5003	0.5483	0.5919	0.6354	0.6318	0.7410							QN2
				0.0655	0.0721	0.0772	0.0776	0.0817	0.0861	0.0927	0.0976							b1
				0.1012	0.0705	0.0791	0.0819	0.0982	0.1051	0.1295	0.2029							b2
				0.5924	0.7389	0.9001	1.0794	1.2733	1.4649	1.6683	1.8101							Qult1
		0	0	13	1912	4085	2444	1028	308	122	11	0	0	0	0	0	0	n
	0.1 - 0.15				0.5781	0.6355	0.6734	0.6717	0.6916	0.6956	0.7060	0.7348	0.7631					QN1
					0.4567	0.5038	0.5564	0.6158	0.6576	0.7104	0.7987	0.7070	0.6309					QN2
					0.1191	0.1201	0.1243	0.1258	0.1276	0.1281	0.1296	0.1328	0.1391					b1
					0.1065	0.1065	0.1124	0.1288	0.1213	0.1339	0.1829	0.1530	0.1540					b2
					0.7457	0.9134	1.0938	1.2901	1.4811	1.6896	1.8826	2.0606	2.2701					Qult1
		0	0	0	847	3169	3103	1889	866	470	219	80	19	0	0	0	0	n
	0.15 - 0.2				0.5653	0.6327	0.6552	0.6696	0.6890	0.6922	0.6788	0.6885	0.7000	0.7801	0.8209			QN1
					0.4621	0.5426	0.5796	0.6220	0.6352	0.6947	0.7525	0.7558	0.8453	0.8560	0.9019			QN2
					0.1679	0.1711	0.1724	0.1735	0.1724	0.1787	0.1753	0.1682	0.1803	0.1852	0.1991			b1
					0.1144	0.1376	0.1505	0.1475	0.1573	0.1631	0.1472	0.1880	0.1941	0.1918	0.2088			b2
					0.7549	0.9188	1.1093	1.2889	1.4863	1.6823	1.8817	2.0945	2.3053	2.4722	2.6246			Qult1
		0	0	0	308	1599	2114	1846	1194	690	277	137	41	30	4	0	0	n
	0.2 - 0.25				0.5551	0.6174	0.6525	0.6749	0.6984	0.7199	0.6966	0.6775	0.7621	0.7370	0.8229	0.8272		QN1
					0.4906	0.5167	0.5792	0.6052	0.6702	0.7428	0.7814	0.7552	0.7745	0.9791	1.0045	1.3680		QN2
					0.2128	0.2187	0.2212	0.2217	0.2235	0.2252	0.2332	0.2301	0.2355	0.2220	0.2023	0.2498		b1
					0.1302	0.1614	0.1745	0.1807	0.2102	0.2028	0.2219	0.1825	0.1774	0.2033	0.3511	0.2641		b2
					0.7721	0.9347	1.1030	1.2981	1.4894	1.6889	1.8868	2.0800	2.2623	2.4631	2.7026	2.8182		Qult1
		0	0	0	104	757	1177	1332	1053	701	372	172	49	22	1	2	0	n
	0.25 - 0.3				0.5522	0.5991	0.6395	0.6808	0.6990	0.6992	0.7044	0.7100	0.6809	0.7720	0.7559	0.8132		QN1
					0.4480	0.4954	0.5593	0.6017	0.6640	0.7341	0.7476	0.7847	0.8190	0.8339	1.0004	1.3724		QN2
					0.2596	0.2717	0.2729	0.2728	0.2745	0.2748	0.2754	0.2751	0.2697	0.2627	0.2847	0.2527		b1
					0.1696	0.1972	0.2301	0.2116	0.2119	0.2256	0.2241	0.2324	0.2460	0.2032	0.2216	0.2632		b2
					0.7697	0.9131	1.1046	1.3003	1.4925	1.6843	1.8855	2.0997	2.2676	2.5215	2.6644	2.8265		Qult1
		0	0	0	18	371	682	889	715	611	359	197	80	24	31	10	0	n
	0.3 - 0.35				0.5447	0.5792	0.6421	0.6730	0.6848	0.7081	0.6820	0.6961	0.7031	0.7175	0.6439	0.7479	0.7235	QN1
					0.4323	0.5376	0.5549	0.6351	0.6496	0.6818	0.7007	0.7054	0.8874	0.9686	0.8754	0.9427	0.9224	QN2
					0.3136	0.3228	0.3235	0.3195	0.3247	0.3195	0.3227	0.3203	0.3293	0.3217	0.3370	0.3323	0.3250	b1
					0.2112	0.1908	0.2173	0.2262	0.2548	0.2321	0.2223	0.2652	0.3306	0.3696	0.3301	0.4829	0.2990	b2
					0.7895	0.9421	1.1041	1.3124	1.4814	1.6849	1.8934	2.0814	2.2818	2.5056	2.6659	2.8529	3.0850	Qult1
		0	0	0	4	204	448	548	541	437	240	244	123	72	39	16	14	n
	> 0.35					0.5810	0.6700	0.6525	0.6961	0.6919	0.7189	0.6785	0.6796	0.7142	0.7001	0.7212	0.7303	QN1
						0.5434	0.5901	0.6353	0.7320	0.6943	0.6934	0.7139	0.7032	0.7566	0.8699	0.8726	1.0330	QN2
						0.3691	0.3706	0.3685	0.3707	0.3714	0.3723	0.3725	0.3679	0.3736	0.3861	0.3803	0.3900	b1
						0.1897	0.2491	0.2453	0.2435	0.2847	0.2758	0.2623	0.2969	0.2233	0.2951	0.3062	0.5307	b2
						0.9122	1.0963	1.3173	1.5078	1.6971	1.8794	2.0981	2.2969	2.4833	2.6929	2.8828	3.0324	Qult1
		0	0	0	0	89	274	334	378	370	257	227	173	88	45	26	17	n

For each subdivision, the median (of all data sets within the segment) of the initial quality and also the deterioration rate before and after the tamping task are indicated. Furthermore, the median of the related intervention level and the number of observations in each segment is stated.

However, instead of the medians and the absolute difference of the values, the relative change in track quality parameters is of great interest for any further consideration. Therefore, the relative changes are computed, and the results are displayed in nine tables in the Annex (Table 26 to Table 34). One of these tables is shown in Table 7 as an example, again for cumulated traffic loads below 225 million gt and initial qualities between 0.54 mm and 0.83 mm. The first line of each segment shows the relative change of the initial quality from one deterioration period to the next under the given boundary conditions. The second line gives information about the change in the deterioration rate. In both cases, a value above one means that the absolute value has fallen.

This equals an improvement of the parameter from one deterioration period to the next. Vice versa, a value below one means a deterioration of the considered parameter. For cases of deterioration, the relative change in the table is marked red.

Table 7: Results (relative) for traffic loads < 225 million gt; Q_{N1} 0.54 mm – 0.83 mm.

		Qult1																
		0 - 0.2	0.2 - 0.4	0.4 - 0.6	0.6 - 0.8	0.8 - 1.0	1.0 - 1.2	1.2 - 1.4	1.4 - 1.6	1.6 - 1.8	1.8 - 2.0	2.0 - 2.2	2.2 - 2.4	2.4 - 2.6	2.6 - 2.8	2.8 - 3.0	> 3.0	
b1	0 - 0.05			1.4108	1.3087	1.3605	1.2788	1.3477										QN1/QN2
				0.8115	0.7321	0.6692	0.5966	0.5291										b1/b2
				1.3322	3.5876	5.2468	8.5933	10.5088										T1
				5.0479	5.1936	6.3924	7.1309	7.7981										T2
				3.7892	1.4476	1.2183	0.8298	0.7421										T2/T1
		0	0	50	763	816	286	39	0	0	0	0	0	0	0	0	0	n
	0.05 - 0.1			1.3835	1.3005	1.2983	1.2391	1.1565	1.1505	1.1980	0.9912							QN1/QN2
				0.6473	1.0228	0.9768	0.9475	0.8318	0.8191	0.7161	0.4812							b1/b2
				0.8094	2.1924	3.2444	5.1578	7.2075	8.5253	9.8316	11.0168							T1
				2.0018	4.1463	5.0564	6.4888	6.9388	7.8932	8.0070	5.2693							T2
				2.4731	1.8912	1.5585	1.2581	0.9627	0.9258	0.8144	0.4783							T2/T1
		0	0	13	1912	4085	2444	1028	308	122	11	0	0	0	0	0	0	n
	0.1 - 0.15				1.2657	1.2614	1.2103	1.0907	1.0517	0.9792	0.8839	1.0394	1.2095					QN1/QN2
					1.1186	1.1273	1.1064	0.9768	1.0517	0.9567	0.7085	0.8680	0.9033					b1/b2
					1.4068	2.3143	3.3819	4.9150	6.1866	7.7598	9.0798	9.9826	10.8310					T1
					2.7133	3.8448	4.7830	5.2347	6.7870	7.3134	5.9256	8.8468	10.6414					T2
					1.9287	1.6614	1.4143	1.0650	1.0971	0.9425	0.6526	0.8862	0.9825					T2/T1
		0	0	0	847	3169	3103	1889	866	470	219	80	19	0	0	0	0	n
	0.15 - 0.2				1.2233	1.1662	1.1304	1.0766	1.0848	0.9964	0.9020	0.9110	0.8282	0.9113	0.9102			QN1/QN2
					1.4670	1.2435	1.1454	1.1759	1.0957	1.0953	1.1909	0.8950	0.9291	0.9653	0.9537			b1/b2
					1.1291	1.6713	2.6343	3.5702	4.6257	5.5414	6.8612	8.3579	8.9019	9.1385	9.0584			T1
					2.5582	2.7332	3.5193	4.5213	5.4104	6.0542	7.6703	7.1224	7.5225	8.4259	8.2508			T2
					2.2656	1.6354	1.3360	1.2664	1.1696	1.0925	1.1179	0.8522	0.8450	0.9220	0.9108			T2/T1
		0	0	0	308	1599	2114	1846	1194	690	277	137	41	30	4	0	0	n
	0.2 - 0.25				1.1315	1.1950	1.1265	1.1152	1.0422	0.9692	0.8915	0.8971	0.9840	0.7527	0.8192	0.6047		QN1/QN2
					1.6352	1.3546	1.2676	1.2270	1.0635	1.1101	1.0507	1.2606	1.3276	1.0919	0.5763	0.9461		b1/b2
					1.0198	1.4508	2.0363	2.8111	3.5382	4.3032	5.1037	6.0951	6.3703	7.7738	9.2919	7.9696		T1
					2.1632	2.5893	3.0011	3.8350	3.8974	4.6639	4.9806	7.2578	8.3876	7.2979	4.8372	5.4918		T2
					2.1212	1.7847	1.4739	1.3642	1.1015	1.0838	0.9759	1.1908	1.3167	0.9388	0.5206	0.6891		T2/T1
		0	0	0	104	757	1177	1332	1053	701	372	172	49	22	1	2	0	n
	0.25 - 0.3				1.2326	1.2095	1.1434	1.1315	1.0528	0.9525	0.9423	0.9049	0.8313	0.9257	0.7556	0.5926		QN1/QN2
					1.5309	1.3775	1.1862	1.2887	1.2955	1.2185	1.2287	1.1840	1.0962	1.2932	1.2851	0.9603		b1/b2
					0.8379	1.1554	1.7044	2.2711	2.8908	3.5844	4.2892	5.0505	5.8839	6.6595	6.7029	7.9659		T1
					1.8969	2.1177	2.3703	3.3007	3.9104	4.2129	5.0773	5.6588	5.8883	8.3071	7.5100	5.5248		T2
					2.2640	1.8329	1.3907	1.4533	1.3527	1.1754	1.1838	1.1204	1.0008	1.2474	1.1204	0.6936		T2/T1
		0	0	0	18	371	682	889	715	611	359	197	80	24	31	10	0	n
	0.3 - 0.35				1.2601	1.0772	1.1573	1.0597	1.0542	1.0386	0.9734	0.9867	0.7923	0.7408	0.7356	0.7934	0.7844	QN1/QN2
					1.4852	1.6915	1.4885	1.4122	1.2741	1.3767	1.4520	1.2078	0.9961	0.8702	1.0209	0.6882	1.0870	b1/b2
					0.7805	1.1246	1.4280	2.0015	2.4534	3.0573	3.7536	4.3253	4.7943	5.5588	5.9997	6.3347	7.2658	T1
					1.6917	2.1198	2.5272	2.9941	3.2641	4.3224	5.3665	5.1886	4.2183	4.1579	5.4239	3.9558	7.2327	T2
					2.1674	1.8850	1.7698	1.4960	1.3304	1.4138	1.4297	1.1996	0.8799	0.7480	0.9040	0.6245	0.9954	T2/T1
		0	0	0	4	204	448	548	541	437	240	244	123	72	39	16	14	n
	> 0.35					1.0693	1.1355	1.0271	0.9510	0.9966	1.0368	0.9504	0.9664	0.9440	0.8048	0.8264	0.7070	QN1/QN2
						1.9461	1.4878	1.5021	1.5225	1.3045	1.3497	1.4203	1.2393	1.6735	1.3083	1.2420	0.7349	b1/b2
						0.8973	1.1504	1.8041	2.1893	2.7066	3.1174	3.8105	4.3962	4.7347	5.1610	5.6838	5.9027	T1
						1.9446	2.0324	2.7801	3.1859	3.5226	4.3000	5.2770	5.3686	7.7338	6.1767	6.5644	3.7677	T2
						2.1673	1.7668	1.5410	1.4552	1.3015	1.3794	1.3849	1.2212	1.6334	1.1968	1.1549	0.6383	T2/T1
		0	0	0	0	89	274	334	378	370	257	227	173	88	45	26	17	n

As already mentioned in chapter 7.2, these evaluations also show that, in many cases, one track geometry parameter improves after the tamping task while the other one deteriorates. This can be demonstrated by taking the red marked segment in Table 7 as an example. For an intervention level between 1.4 mm and 1.6 mm and a deterioration rate between 0.05 and 0.1 mm per year, the initial quality improves by the factor of 1.1505 in the next deterioration period. In contrast, the degradation rate deteriorates by a factor of 0.8191 on average. In this case, it is quite difficult to assess the total consequences for the next deterioration period. This results in questions such as: “Is a deterioration in one parameter compensated by the improvement of the other value?” or “Is it better to generate small improvements for both parameters or to improve one parameter considerably while the other value deteriorates slightly?” To answer such questions, it is necessary to combine the information of the two parameters into one message.

Therefore, the tamping interval can be used which equals the (fictitious) length of the deterioration period. For the first deterioration period, the parameters Q_{N1}, b_1, and Q_{ult1} are known, which allows for the calculation of the tamping interval T_1 as follows:

$$T_1 = \frac{Q_{ult1} - Q_{N1}}{b_1} \tag{29}$$

For the second deterioration period, the initial quality Q_{N2} and the deterioration rate b_2 can be calculated using the results from the above-mentioned tables. Though, the intervention level for the second period is unknown at the present moment. Therefore, the intervention level of the first period is used, which makes it also more reliable to compare the results of the consecutive periods. The tamping interval T_2 for the second deterioration period can be calculated by the formula:

$$T_2 = \frac{Q_{ult1} - Q_{N2}}{b_2} \tag{30}$$

The basic principle of this methodology is demonstrated in Figure 49. Table 7 shows the tamping intervals for the first (T_1) and the second (T_2) deterioration period in the third and fourth line for each segment. The comparison of the two tamping intervals makes it possible to evaluate the impacts of a tamping intervention on track quality behaviour in an overall way. This is visible in the fifth line of Table 7 for each subdivision. A value above one means that the tamping interval increases. This equals an overall improvement of the track quality parameters. Vice versa, a value below one represents a shorter tamping interval after the intervention, which means an overall deterioration.

For the example in the area marked red, an improvement in initial quality and an increase in deterioration rate was determined at first. A comparison of the tamping intervals shows that in total a deterioration of the track quality parameters has to be expected as the tamping interval decreases by the factor of 0.9258.

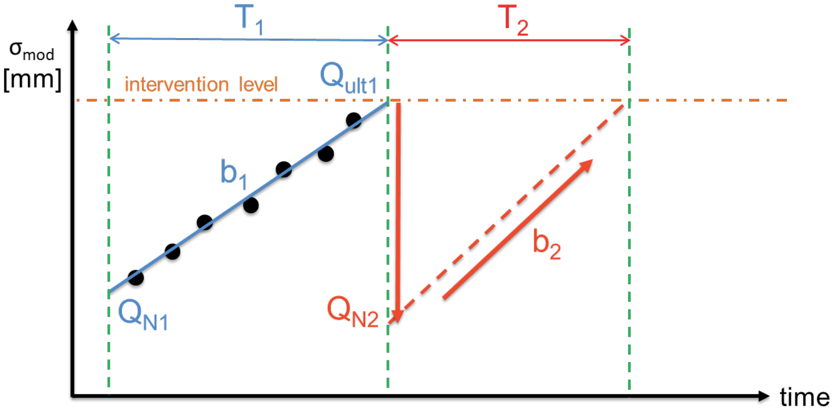


Figure 49: Change in track quality parameters after tamping and related tamping intervals.

Based on the methodology and results presented in this chapter, it is now possible to estimate track quality parameters after a tamping intervention under the given boundary conditions. The overall trends of the evaluations show that general deteriorations have to be expected in particular for tracks with very good initial quality, for old tracks and in the event of (excessively) late or a very early intervention. Vice versa, improvements can be achieved especially for young tracks, tracks with poor initial quality and for medium intervention levels.

8

Tamping strategy

The methodology and the related results from chapter 7 provide the opportunity to estimate the consequences of a tamping intervention on track quality behaviour. This information makes it possible to predict more than the next tamping task, as the required track quality parameters can be estimated based on the given boundary conditions. Furthermore, it is possible to estimate the track quality parameters of a present deterioration period in the event of too few measuring points for calculating a regression. The only requirement are reliable track quality parameters from the last deterioration period.

The main goal of the present chapter is to go one step further and develop a sustainable tamping strategy for the given circumstances. It must be stated that a tamping strategy is inseparably associated with the choice of the (right) intervention level (ILE).

8.1 Optimal intervention level

Within a reactive maintenance regime, failures are corrected in the event of exceeding a specific limit value. This strategy causes a comparable low amount of interventions, but the fixation of the failure cannot be planned and has to be carried out immediately to guarantee safety and availability. Furthermore, the overall track quality is quite poor as only safety critical failures are repaired. A cyclic maintenance regime provides a better overall track quality, as longer sections are maintained in fixed time intervals. However, the condition of the track is not included in the considerations.

Therefore, on the one hand, this strategy may also cause unplanned and immediate interventions in the case of any exceeded limit values. On the other hand, sections are maintained where it is not necessary. This might cause unnecessary interventions in a working system, and budgets are spent very ineffectively. Hence, it must be the goal to find a strategy where maintenance is carried out at the optimal point in time for the total system.

Considerations for finding an optimal intervention level exist since reproducible data from the measuring car are available. These data are a necessary precondition to show the consequences of tamping interventions as described in chapter 7. First concepts for optimising the intervention level are formulated by Veit [126]. As the processing and analyses of measuring data was in its infancy at this time, the considerations are more qualitative in nature. The idea is thus formulated that the intervention level must have significant influence on the reachable service life. As the initial quality after a task seems to decrease exponentially over time, it is assumed that a non-constant intervention level must have positive influence on service life.

Initial quantitative investigations regarding an optimal intervention level are executed by Auer [127]. Within this thesis, a prediction model for track quality behaviour over time is tested as a first step. Afterwards, the influence of the intervention level on the service life of the track is examined. The results indicate that a compliant intervention level stretches service life by four percent compared to a constant and by eight percent compared to an opposed intervention level. Applying a compliant intervention level therefore leads to economic benefits. The results are verified by varying the input parameters as well as the calculation model itself. However, it must be stated that the data basis for the analyses is quite limited. Furthermore, only few track parameters (track quality, track age, superstructure) are considered. Although general recommendations for the nature of the intervention level are given, no quantitative statements regarding the optimal values are made.

Hummitzsch [27] develops a prediction model to assess track quality behaviour over the service life under different boundary conditions. Within the investigations, also the differences between a constant and a compliant intervention level are analysed. The results show that it is possible to prolong service life by applying a compliant intervention level. However, in this study, the comparison is done only for one set of parameters. This means any additional potential influencing factors on the result are neglected. Furthermore, the analyses by Hummitzsch [27] and also by Holzfeind [122] demonstrate that an improvement of the initial quality from one deterioration period to the next may lead to a sharp increase in the deterioration rate.

In total, this effect of “tamping too early” may lead to significant reductions in service life. Also, the results from these studies are related to general statements, and no detailed values for optimal intervention levels are indicated.

The examinations from Hansmann [123] analyse different dependencies of track quality parameters before and after tamping interventions. Afterwards, the results are clustered and the consequences of different tamping intervals are determined for every cluster. Thus, it is possible to detect the tamping interval (time span between the last and the next intervention) with the best impact on track quality parameters after tamping. However, the determination of the optimal tamping interval still requires some subjective assumptions. Therefore, a direct transfer of the results on real data is only possible by executing additional detail analyses. Furthermore, no tamping intervals above six years are considered.

The analyses above show that it was not yet possible to find an optimal intervention level in a quantitative way that can be used for the whole service life of any track. The elaborated tables in chapter 7.4 show all the relevant dependencies of track quality parameters before and after tamping. Therefore, they seem to be a reliable foundation to determine the optimal intervention level for the given boundary conditions.

At first sight, it would be obvious to use a similar method as by Hansmann [123] and choose the intervention level that delivers the best quality parameters in the next deterioration period. In the present case, that would be very easy as the alteration in initial quality and deterioration rate are summarised in the change of the tamping intervals (T_2/T_1). This means the optimal intervention level would be the value that leads to the highest value for T_2/T_1. However, it must be considered that this approach optimises the track quality parameters for the next deterioration period, nothing more. In general, the best ratios for T_2/T_1 can be reached for quite low intervention levels. This strategy would lead to lots of interventions. Therefore, it must be questioned whether it is even necessary to always reach the best possible quality in the subsequent period. Furthermore, a lot of tamping tasks are quite costly and require a high amount of track possessions, which has negative effects on availability. Last but not least, the tamping process itself applies mechanical stresses to the ballast bed and causes a certain quantity of ballast pollution. Hence, it is not possible to execute an unlimited number of tamping tasks also for technical reasons. In general, this means it is not enough to consider only the consequences of a tamping task on the following deterioration period. It is much more necessary to take a look at the track quality behaviour of the whole life span to determine an optimal intervention level. This task is the goal of the following chapters.

8.2 Excursus: How many tamping tasks are possible for a railway track?

Before different tamping strategies can be checked, it is necessary to define the number of tamping tasks that can be executed within the life cycle. This number has to be the same for all analysed strategies in order to permit reliable comparisons.

Within a study [128] the contribution of tamping tasks to ballast pollution is examined based on a detailed literature review. For the review, the analysed experiments are divided into two groups: the first group only considers mechanical stresses due to tamping intervention and the second group contains strains due to tamping and also loads from train operation. The different experiments are described briefly in the following and the results are summarised in Table 8.

A rather comprehensive study regarding ballast pollution due to tamping tasks was executed in Switzerland [3]. For this experiment, two side tracks in a railway station were equipped with two different types of ballast. Afterwards the tracks were divided into five sectors and the sectors were encumbered with different numbers of tamping processes. After the execution of the tamping tasks, samples from the tamping area in the ballast bed were taken and analysed. The results show that ballast pollution (defined as the grain fraction < 22.4 mm) increases linearly with the number of squeezing processes. After 28 squeezing processes, a degree of ballast pollution between 30 % and 35 % was observed.

These results correspond approximately to the value of 30 % at which ballast cleaning should be executed [129] [130]. This means a railway track would tolerate about 28 tamping processes with one or 14 tamping processes with two squeezing tasks.

Within the experiments from Douglas [131] , laboratory tests were executed to investigate the process of ballast pollution due to tamping tasks. Therefore, different types of ballast were filled in a box and a wooden sleeper was placed above. Over the box, a tamping unit was attached that encumbered different numbers of tamping processes. Before and after every sub-experiment, the grain size distribution was determined. The results showed a very low amount of grain sizes < 1 inch which was defined as ballast pollution in this case. By extrapolating the degree of pollution up to a value of 30 %, it would turn out that more than 1,000 tamping tasks could be executed until the value is reached. Furthermore, it could be demonstrated that the increase of ballast pollution decreases with the number of tamping tasks.

Another field experiment to investigate this topic was executed in a side track of a railway station in France [132]. For these tests, big bags with ballast for LGV lines were placed under the sleepers (Figure 50).

Afterwards, the ballast was tamped between 0 and 45 times. The next step was to remove the big bags and to investigate the ballast regarding its grain size distribution. The results showed that especially the grains with a size of 50 mm and bigger are influenced by the tamping process and break into the next smaller grain size class. In contrast, the formation of fines (no detailed definition of fines is given) plays a subordinate role. After 45 tamping processes only 0.38 % of fines occur. Extrapolating this result to a degree of pollution of 30 %, this would indicate that 3,550 tamping tasks could be executed before the value is reached.

Figure 50: Test setup of the tamping experiments in [132].

Within the experiments in [133] and [134] the consequences of stresses due to the tamping process on lime stone and granite were tested. The ballast and sleepers were placed in a box and in total 20 tamping processes were applied. After 10 and 20 tamping actions, the grain size distribution was measured. The results indicate a significant, more or less linear, increase of ballast pollution (measured on the ¼-inch sieve representing 6.35 mm) due to the tamping activities. For the harder granite, a significant lower degree of pollution was measured. By extrapolating the measured pollution, for limestone 63 and for granite 120 tamping processes would be possible until a critical value of (in this case) 20 % is reached.

The above described experiments focus only on the consequences of tamping processes on ballast pollution. In contrast to that, besides the tamping forces, the following examinations also include stresses due to train operation. The first experiment is the Vibrogir test, where six types of ballast were investigated within a round robin test [135]. The Vibrogir device applies wave-shaped movements on the sleepers to simulate the stresses from train operation. At the beginning and during the experiment, tamping tasks were also executed to limit rail deflection. In total, between 6 and 17 tamping processes were applied.

After the tests, the grain size distribution was determined and showed degrees of pollution (< 22.4 mm) between 3 % and 5.9 %. A linear extrapolation would lead to a number of possible tamping tasks between 59 and 318 until 30 % pollution are reached.

Within another large-scale test in Switzerland by Paderno et al. [136], stresses due to tamping tasks as well as train operation were simulated. Therefore, a test track with a length of 19 m and two different types of subsoil was constructed in a laboratory. Stresses due to train traffic were simulated by means of a hydraulic press (Figure 51). After a load cycle of 45 million tons, a tamping process was executed. After a load cycle and also after every tamping process, load plate pressure tests were conducted, and the corresponding deformation modules were calculated. Based on this information the instability could be determined. The results show that the instability after the tamping process is much higher compared to the load cycle. Furthermore, the instability was lower for higher penetration depths, and a better ballast performance could be reached by means of tamping with higher frequencies. Regrettably, in the study no statements regarding the grain size distribution before or after the applications of the different stresses were made. Therefore, it is not possible to derive any information about ballast pollution due to tamping tasks and/or train operation.

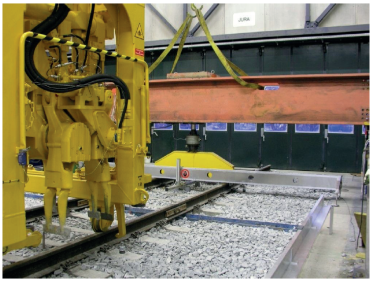


Figure 51: Test setup with a tamping unit and the hydraulic press [136].

During a field test in the USA [137] [138], new dolomite ballast was installed within a test section on a main line. After one, two and three years of railway operation, the grain size distribution was investigated. Furthermore, after three years a tamping task was executed and also after the tamping action the sieving curve was determined. The results show that the ballast pollution (in this case < 4.76 mm) increases linearly due to railway operation and reaches a value of 5 % after three years. After the tamping task, the degree of pollution increases abruptly to 8.5 %. Considering a critical value of 30 % in this case, it would be possible to execute nine tamping processes until this value is reached. If the loads due to train traffic are also considered, only five tamping tasks are possible until the critical degree of pollution is exceeded.

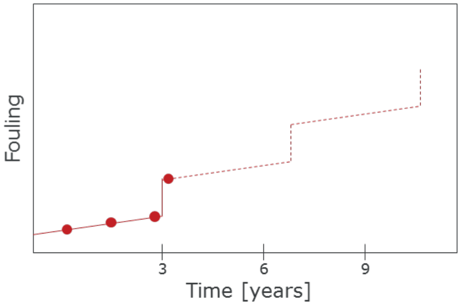


Figure 52: Schematic development of ballast pollution:
linear increase due to train operation and sudden increase due to tamping process.

In Switzerland, ballast samples were investigated for tracks that showed early signs of ballast aging [139]. The results demonstrated that the highest degree of ballast pollution can be found in the tamping area of the ballast bed. In contrast, the ballast directly under the sleeper showed quite good condition in most cases. A higher degree of pollution under the sleeper was only found in case of poor ballast quality and in areas of insulated joints where high impact forces occur.

In Great Britain, two different experiments were executed to identify the consequences of train operation [140] and mechanical stresses due to tamping actions [141] on ballast pollution. For simulating train operation, ballast was put in a wooden box together with a model of a sleeper. Afterwards, a pulsating force was applied that should simulate different axle loads. After a specific amount of load cycles, the resulting ballast pollution was measured. Through interpolation, for an axle load of 22.5 t, an amount of 4.2 kg of fines (in this case < 14 mm) can be determined after 1 million load cycles. In a separate test, the influence of tamping tasks on the ballast pollution was investigated. Therefore, wooden boxes with ballast were placed under the sleepers in a railway track. Afterwards, ten tamping processes were applied, and the amount of fines was analysed. In this case, up to 3.9 kg of fines are produced. By extrapolating this value, 34 tamping tasks can be executed until the critical value of 30 % of ballast pollution is reached (assumption: 400 kg ballast under the sleeper [132]). By also including the stresses due to train operation, eleven load cycles with a following tamping intervention (assumption: tamping every 2 million load cycles, 45 million t, respectively) can be applied.

The results of the different experiments and studies are summarised in Table 8. The table contains information regarding the type of applied loads, the type of the experiment in general (lab or field test), execution of an LA test, number of analysed ballast types, the definition of ballast pollution and the number of tamping processes within the study.

Besides a short description of the results, the determined or extrapolated number of possible tamping processes (penetration processes) is indicated. Furthermore, the table shows the relation of stresses due to tamping and train operation regarding the causation of ballast pollution. It must be stated that the comparison of the results from the different experiments must be done carefully, as the definition of ballast pollution and also the ballast quality vary considerably in some cases.

The overview of the results shows that it is quite difficult to identify a reliable proportion between the ballast pollution causing factors. In total, only three studies make it possible to calculate such a relation, delivering quite different results. Furthermore, it must be stated that only the study by AAR [137] and Chrismer [138] considers stresses due to tamping and train operation on the same section. The analyses by Röthlisberger et al. [139] of the two types of stresses were executed for different sections, and afterwards the results were compared. Also the results from Johnson et al. [140] and Wright [141] come from different experiments and were aggregated to an overall statement in the end. Hence it is not possible to indicate clearly in which relation stresses due to tamping processes and train operation contribute to ballast pollution. To answer this question, it would be necessary to execute mid- to long-term experiments where both stresses are applied to the same track section and the degree of ballast pollution has to be monitored regularly.

Another important question of the study was related to the influence of ballast pollution due to tamping tasks on the service life of the track. Although the results regarding the maximal possible tamping processes vary widely, a limitation of service life need not to be expected only due to tamping. However, train operation also causes ballast pollution and requires tamping tasks to correct track geometry failures. Therefore, both types of stresses have to be considered as a combination. For the further analyses, it is assumed that a track is tamped ten times during the service life. This value should not be considered as a fixed number of possible tamping tasks after which the ballast has to be replaced in any case. It is much more a consistent value to allow for comparisons of different tamping strategies. Hence, also the calculated corresponding service lives should not be regarded as a fixed value but much more as a base for comparisons. Nevertheless, an average number of ten tamping tasks seems to be realistic due to the results in Table 8 where both types of stresses are considered.

This corresponds also with analyses on the standard elements of the Austrian tracks. These investigations show a tamping demand of between 10 and 15 times within the entire service life for the Austrian ballast quality and transport loads. This is not true for special situations like single failures or track on soft soil where more tamping needs to be executed.

Table 8: Summary of the results from the different tamping experiments.

	stresses due to tamping	stresses due to train operation	laboratory test	field test	LA-test	analysed ballast types	definition pollution	result	possible # tamping proc. (squeezing proc.)	relation tamping/train operation	# tamping processes in tests
Switzerland, Röthlisberger, from 1998	✓	✗	✗	✓	✓	2	< 22.4 mm	degree of pollution 30 % - 35 % after 14 (28) tamping processes	14 (28)	✗	14 (28)
USA, Douglas 2013	✓	✗	✓	✗	✓	13	< 25 mm (1´´)	increase in pollution: 0.42% at 12; 0.36% at 25; 0.22% at 62; 0.17% at 100 tamping processes no correlation between LA-test and "tamping resistance"	1013 (2026)	✗	12, 25, 62, 100
France, 2011	✓	✗	✗	✓	✗	1	"fines" certainly < 25 mm	only 0.38 % pollution after 45 tamping processes	3 550	✗	45
USA	✓	✗	✗	✓	✗	2	< 6.35 mm (1/4´´)	between 5 % (granite) and 9.5% (lime stone) pollution after 20 tamping processes	63 bzw. 120	✗	20
ERRI, Beginning 1990s	✓	✓	✓	✗	✓	6	dep. on test (< 22.4 mm!)	LA-test suitable to describe strength properties of track´s ballast; 3% to 5.9% pollution after the test	59 - 318 (incl. to)	✗	betw. 6 and 17
Switzerland, Paderno, 2011	✓	✓	✓	✗	✗	?	✗	after tamping in most cases higher instability than after load-cycles of train traffic	✗	✗	?
USA, Associaton of American Railroads	✓	✓	✗	✓	✗	1 (3)	< 4.76 mm (no.4 sieve)	after 3 years of train traffic 5 % pollution; after tamping after 3 years: increase to 8.5 %	9 (incl. to: 5)	ca: 60/40	1
Switzerland, Röthlisberger, 1997	✓	✓	✗	✓	✓	?	< 22.4 mm	crit. area for aging of track´s ballast is "tamping area"; no correlation between LA-test and "tamping resistance"; DAH seems to be suitable to descirbe tamping-stresses	✗	quasi 100/0	?
Great Britain, 1980s	✓	✓	✓	✓	✗	3 / 1	< 14 mm	due to one tamping task per sleeper 1.8 to 3.9 kg of the fraction < 14 mm occur; after 1 mio. load cycles with 22.5 t axle load 4.2 kg of the fraction < 14 mm occur	34 (incl. to: 11)	ca: 30/70	10

8.3 Finding the optimal intervention level

To find the optimal intervention level, the consequences and therefore the track quality behaviour over the whole life cycle have to be considered. In all the following analyses, the life span is defined with the time until ten tamping tasks are reached to create a comparable situation for all cases (chapter 8.2). To increase the clarity of the results, the service life is stated in years. However, the calculations in the background are executed with the cumulated traffic load. To convert the results from one unit to the other, a traffic load of 50,000 gt per day and track is assumed. As a first step, the analyses are done for two examples with strongly different track quality properties: a “poor track” with a low initial quality and high deterioration rate, and a “good track” with a high initial quality and low deterioration rate. In a subsequent step, the results from the two examples are checked for generality and the methodology is validated.

8.3.1 Track with poor quality

At first, the track quality behaviour with different intervention levels is tested for a “poor track”. The “poor track” is defined by quite a low initial quality of 1.08 mm and a high deterioration rate of 0.38 mm/year. Both values belong to the worst 30 % of the respective network-wide distributions. Furthermore, for the first analysis, a constant intervention level of 1.55 is chosen. Based on this information, it is possible to determine the point in time at which the first tamping task has to be executed. With the initial quality and the deterioration rate of the first deterioration period together with the intervention level and the cumulated traffic load at the point in time of intervention, it is possible to calculate the track quality parameters for the next period. Therefore, the findings and developed tables in chapter 7.4 are used. This procedure is repeated until ten fictitious tamping tasks are executed. The ensuing picture of track quality behaviour over time is shown in Figure 53. After reaching the intervention level in the tenth period, the resulting service life can be indicated. In the present case, a service life of 38 years is the result.

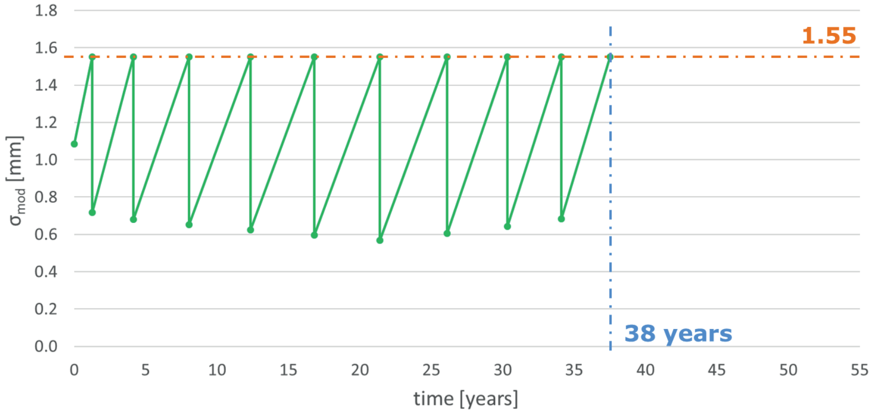


Figure 53: Track quality behaviour for a "poor track" with a constant intervention level.

As described in chapter 8.1, many studies indicate that using a compliant instead of a constant intervention level makes it possible to stretch the service life significantly. To test this finding, a compliant intervention level is applied to the same data set as before. It is assumed that for the first three tamping interventions the intervention level is decreased to 1.15 mm. For the further tamping tasks, a limit value of 1.55 mm is used again. The related track quality behaviour over time is shown in Figure 54. As a result, the service life yields to a value of 35 years. Compared to the constant intervention level, this is an impairment of three years in service life. Obviously, the strategy of using a compliant intervention level is not reasonable for a track with the given boundary conditions.

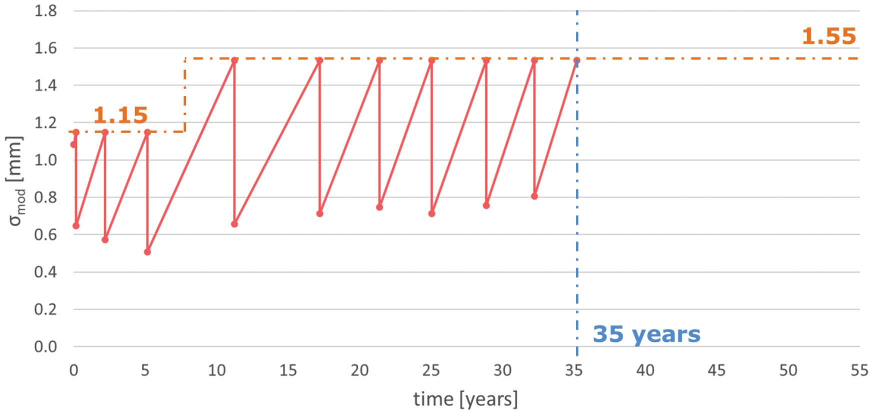


Figure 54: Track quality behaviour for a "poor track" with a compliant intervention level.

Within an additional examination, the following question is addressed: What happens if anytime the intervention level is chosen that provides the best track quality parameters in the next deterioration period. Therefore, the same data set is analysed as before. The results are depicted in Figure 55 and demonstrate that ten tamping tasks are already reached after 24 years. After the first tamping action, a more or less constant intervention level of 0.7 mm must be applied to fulfil the strategy. The results impressively show that it is theoretically possible to improve track quality parameters significantly even though the initial quality is poor. However, the effort is very high, and the reduction in service life is significant. The present strategy might be an option to reach a desired track quality due to some few interventions. That said, the permanent optimisation of track quality over service life is not suitable, as it does not allow the mid- to long-term advantages of the achieved improvements to be taken.

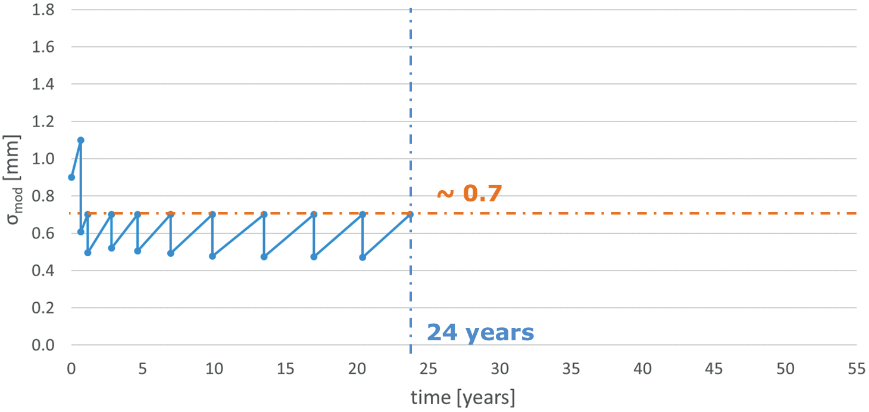


Figure 55: Track quality behaviour for a "poor track" with the intervention level for the best track quality in the next deterioration period.

8.3.2 Track with good quality

In contrast to the last chapter, now “good tracks” are the subject of investigation. “Good tracks” are defined by a high initial quality of 0.42 mm and a low deterioration rate of 0.12 mm/year. In this case, both values belong to the best 30 % of the respective network-wide distribution. For the present investigations, the same methodology is used as in chapter 8.3.1. The first analysis once again concerns the strategy of a constant intervention level. For reasons of comparison, the same value of 1.55 mm is chosen. The resulting course over the service life is depicted in Figure 56.

As shown in the graph, by applying the strategy of a constant intervention level, a service life of 40 years can be generated in this case. Compared to the results of the “poor track”, this means a prolongation in service life of only two years.

This result would contradict the assumption that initial quality is of great importance to reach a long service life to optimise life cycle costs [113]. Hence, the strategy of applying a constant intervention level to tracks with good quality does not seem to be reasonable.

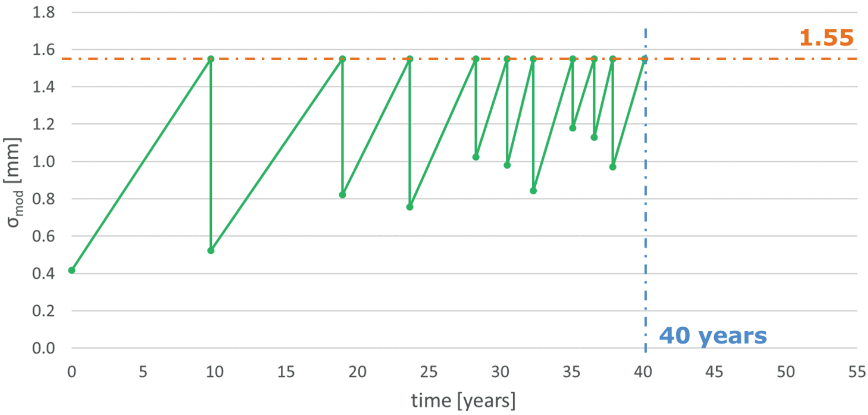


Figure 56: Track quality behaviour for a "good track" with a constant intervention level.

In the next step, a compliant intervention level is tested for the “good track”. Once again, the same parameters are applied as in chapter 8.3.1. This means, for the first three tamping tasks, the intervention level is set to 1.15 mm and afterwards increased by one third to a value of 1.5 mm. The results of this example are depicted in Figure 57. Now, it is possible to increase the service life up to 49 years. This means a significant improvement compared to all analysed cases of the “poor track” and also in relation to the strategy of a constant intervention level for the “good track”.

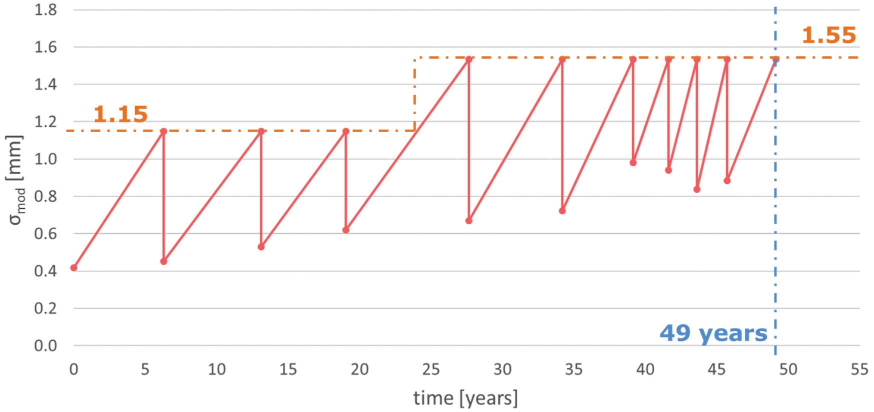


Figure 57: Track quality behaviour for a "good track" with a compliant intervention level.

The results indicate that there is a big potential for stretching service life due to choosing an optimal intervention level. However, all the previous analyses are only executed with the same parameter set. Therefore, some further investigations are also performed where the parameters for the compliant intervention level are varied. Meanwhile, the input values for track quality (initial quality and deterioration rate) are left unchanged. The results show that there is further potential to stretch the service life even more by choosing the right parameters. Figure 58 shows an example where the intervention level is set to a value of 1.05 mm at the beginning and increases to 1.75 mm after four tamping tasks. This configuration leads to a reachable service life of 53 years after ten tamping interventions, which means an additional improvement of four years compared to the example in Figure 57.

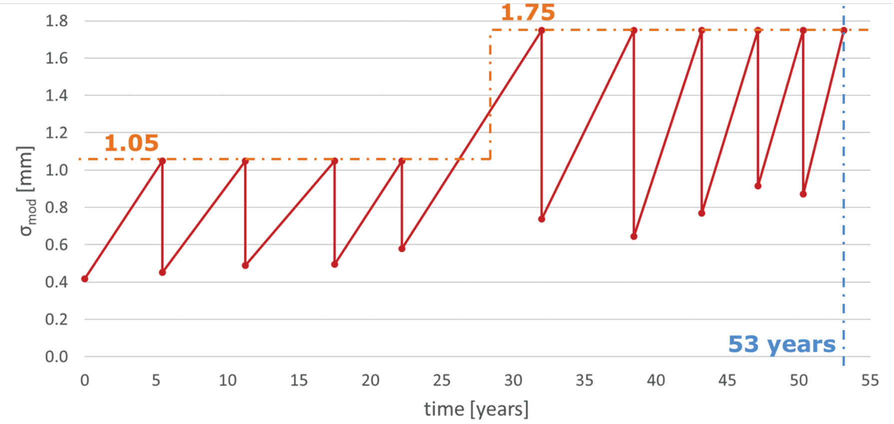


Figure 58: Track quality behaviour for a "good track" with an optimised compliant intervention level.

8.3.3 Validation

The evaluations in chapter 8.3.1 and 8.3.2 are executed for two quite different sets of input parameters. Despite the low number of distinction cases, it is already possible to derive some key findings and tendencies. Nevertheless, to check the results for general validity and to extend the results for any combination of input parameters, further analyses are necessary.

To perform these examinations, a source code is generated with the software "*R*" (chapter 9.2). This code allows for the determination of the resulting service life for any input parameters combined with any intervention level. Within the code, constant as well as compliant intervention levels can be considered.

With the help of this program, it is possible for the first time to calculate the optimal intervention level for any boundary conditions automatically. The optimal intervention level is the value where the highest service life results for the given input parameters. This means, by knowing the initial quality and the deterioration rate of the first deterioration period, it is possible to calculate the optimal intervention level for the whole life cycle.

To test different strategies in an overall way, it is necessary to define characteristic input parameters for the initial quality and the deterioration rate for the first period. Therefore, for the two parameters, the network-wide 16.7 %, 25 %, 33.3 %, 50 %, 66 %, 75 % and 83.3 % quantiles are determined for the first periods.

The resulting values can be found in the black marked boxes in Table 9. Afterwards, with all possible combinations of the values, the optimal constant intervention level is calculated. Table 9 indicates the optimal intervention levels together with the corresponding reachable service life.

Table 9: Optimal constant intervention level for different combinations of Q_N and b.

		Q_N							
		16.7% 0.362	25.0% 0.418	33.3% 0.472	50.0% 0.611	66.6% 0.794	75.0% 0.928	83.3% 1.083	
b	16.7% 0.089	1.15 50.65	1.35 53.34	1.35 45.95	1.35 46.11	1.35 51.05	1.95 48.46	2.15 57.73	opt. ILE SL
	25.0% 0.116	1.35 54.26	1.35 50.86	1.35 46.9	1.75 50.56	2.15 52.2	1.35 48.23	2.15 49.13	opt. ILE SL
	33.3% 0.142	1.75 49.72	1.75 51.05	1.75 46.09	1.35 42.59	1.65 44.02	1.95 46.21	1.95 44.4	opt. ILE SL
	50.0% 0.210	1.95 44.94	1.95 46.53	1.95 44.91	1.55 42.56	1.95 43.7	1.95 44.38	2.75 42.39	opt. ILE SL
	66.0% 0.303	1.55 43.12	1.35 41.35	1.35 39.84	1.35 40.57	1.95 40.22	1.95 41.18	1.35 36.95	opt. ILE SL
	75.0% 0.376	1.95 41.24	1.55 39.23	1.55 38.82	1.95 44.14	1.55 38.25	1.95 41.18	1.85 37.62	opt. ILE SL
	83.3% 0.478	1.95 42.23	1.85 38.05	1.95 38.29	1.95 42.71	1.95 39.89	1.35 34.35	2.25 38.52	opt. ILE SL

The green marked area includes results for tracks with good initial quality parameters. By summarising the values, an average intervention level of 1.46 mm and an average service life of 49.86 years can be indicated. The area within the dark red boarder contains tracks with quite poor quality parameters at the beginning of the service life. On average, an optimal intervention level of 1.79 mm and a corresponding service life of 38.68 years is the result. The areas marked with light red borders contain tracks, where one track quality parameter is quite good and the other parameter quite poor at the beginning of the service life. For these tracks, the optimal intervention level is 1.86 mm on average and an intermediate service life of 45.53 years can be indicated. By optimising the constant intervention level, the results show that it is reasonable to introduce a lower intervention level for tracks of good quality. In cases of at least one poor value, higher intervention levels must be applied to maximise service life.

However, by applying the optimal constant intervention level under the given boundary conditions, tracks with good initial quality parameters show significant longer service lives. This result confirms the great importance of a high initial quality.

In a subsequent step, the same evaluations are performed for the compliant intervention level. To define this, for the first three tamping tasks, a lower level is utilised and afterwards increases by one third.

As the results showed quite similar results and therefore do not provide any additional information, the values of the 25 % and 75 % quantile are omitted in the further considerations. Thus, the results for the values that represent the 16.7 %, 33.3 %, 50 %, 66.6 % and 83.3 % quantile of the two track quality parameters are shown in Table 10. Within the table, the results of the different combinations are marked with colours. A green field means that it is possible to prolong the service life by more than two years due to using the optimal compliant ILE instead of the best constant ILE. In contrast to that, a red field stands for a shortening in service life by more than two years by applying the optimal compliant intervention level. Fields in white indicate that there is no significant difference by changing the optimal constant ILE to the optimal compliant ILE. The results impressively show that compliant intervention levels in particular lead to significant improvements for tracks with good initial quality parameters. For tracks that exhibit poor values for one or both parameters, the utilisation of the compliant ILE leads rather to shortenings in service life, or the situation remains unchanged. Again, in general, for tracks with good parameters, lower intervention levels are indicated than for tracks with poor parameters. Generally speaking, the results show that the compliant intervention level should be used for “good tracks”, as there is great potential for stretching the service life. By contrast, for “poor tracks”, a (high) constant ILE is the more reasonable option to optimise service life under the given conditions.

Table 10: Optimal compliant intervention levels for different combinations of Q_N and b.

		Q_N					
		16.7% 0.362	33.3% 0.472	50.0% 0.611	66.6% 0.794	83.3% 1.083	
b	16.7% 0.089	0.75/1.00 64.2	0.75/1.00 58.32	1.65/2.20 58.45	1.75/2.33 51.79	1.35/1.80 52.42	opt. ILE SL
	33.3% 0.142	1.05/1.40 48.38	1.65/2.20 48.69	1.45/1.93 46.69	1.65/2.20 46.23	1.35/1.8 39.96	opt. ILE SL
	50.0% 0.210	1.35/1.80 47.96	1.65/2.20 49.35	1.65/2.20 48.56	1.45/1.93 41.42	1.55/2.06 42.94	opt. ILE SL
	66.0% 0.303	1.05/1.40 40.44	1.45/1.93 42.44	1.35/1.80 42.31	1.45/1.93 39.14	1.15/1.53 35.77	opt. ILE SL
	83.3% 0.478	1.65/2.20 43.99	1.55/2.07 41.14	1.45/1.93 38.28	1.35/1.80 37.57	1.45/1.93 36.63	opt. ILE SL

It must be stated that the compliant intervention level is not a fixed combination in general; it is much more a composition of several variable factors. Besides the intervention level for the first tasks, there is also the question of how much the ILE should be raised later. Additionally, it must be defined after how many tamping tasks the increase in the value should be applied. Furthermore, it is of interest whether the ILE should be increased at one point in time, or if it is more reasonable to do it in steps.

To answer these questions, some sensitivity analyses with varying parameters are carried out. The examinations are performed for the values of the 16.7 %, 50 % and 83.3 % quantile. Afterwards, the results are compared with the base scenario where the intervention level increases by the factor of 1.33 after three tamping tasks.

At first, the sensitivity of the results regarding the factor for increasing the intervention level is checked. Therefore, the factor is adapted to 1.2 in one case and to 1.5 in the other case. The results are depicted in Table 11. This time, the colour indicates the change in service life (>+2 years green, <+2 and >-2 white, <-2 red) compared to the results of the base scenario related to the compliant intervention level (Table 10). As the results show, in most cases, there is no significant difference due to the change of the factor. Especially for low deterioration rates, there is even a detectable deterioration.

Table 11: Optimal compliant intervention level for an increase factor of 1.2 (a) and 1.5 (b) after three tamping tasks.

(a)		Q_N			
		16.7% 0.362	50.0% 0.611	83.3% 1.083	
b	16.7% 0.089	1.15/1.38 59.99	1.65/1.98 51.78	1.45/1.74 48.65	opt. ILE SL
	50.0% 0.210	1.45/1.74 46.9	1.75/2.10 47.66	1.75/2.10 45.9	opt. ILE SL
	83.3% 0.478	1.75/2.10 42.21	1.65/1.98 39.94	1.15/1.38 37.51	opt. ILE SL

(b)		Q_N			
		16.7% 0.362	50.0% 0.611	83.3% 1.083	
b	16.7% 0.089	0.65/0.98 64.06	1.45/2.22 50.72	1.15/1.73 49.05	opt. ILE SL
	50.0% 0.210	1.25/1.88 49	1.25/1.88 43.78	1.45/2.18 44.08	opt. ILE SL
	83.3% 0.478	1.55/2.33 44.96	1.25/1.88 39.64	1.45/2.18 36.12	opt. ILE SL

In the next step, the number of tamping tasks is varied after that the intervention level increases from the lower to the upper one. The value is increased from three tasks in the base scenario to five tasks. Afterwards, the results of the optimal intervention levels and their related service lives are compared to the base scenario in Table 10. The results in Table 12 show that, especially for good tracks, the variation of the point in time at which the ILE is increased leads to a shortened service life. Conversely, for tracks with poor quality parameters, a longer service life is reachable. However, this improvement leads to quite similar values as by applying the constant intervention level. In total, it can be stated that the variation of the point in time at which the intervention level is increased only improves the situation for tracks where actually a constant intervention level should be applied. For “good tracks”, where a compliant ILE is generally reasonable, the present adaption only brings a disadvantage.

Table 12: Optimal compliant intervention level for an increase factor of 1.33 after five tamping tasks.

		Q_N			
		16.7% 0.362	50.0% 0.611	83.3% 1.083	
b	16.7% 0.089	0.75/1.00 60.66	1.35/1.80 51.96	1.35/1.80 57.81	opt. ILE SL
	50.0% 0.210	1.35/1.80 46.2	1.55/2.07 50.78	1.35/1.80 44.18	opt. ILE SL
	83.3% 0.478	1.75/2.33 41.49	1.35/1.80 40.67	1.75/2.33 38.78	opt. ILE SL

The next variations are related to the number of increases of the intervention level. Instead of one, within the next analyses, two increases are applied step wise and again, the results are compared to the base scenario in Table 10. To investigate the sensitivities, three cases are analysed. The first case increases the ILE after three tamping tasks by the factor of 1.33 and after five actions by the factor of 1.5. The second case applies a factor of 1.2 after three and a factor of 1.33 after five tamping tasks. The third case raises the intervention level by a factor of 1.2 after two and a factor of 1.33 after four tamping tasks. The results are depicted in Table 13 and show quite a similar characteristic as the analyses before.

Table 13: Optimal compliant intervention level with two increases of ILE: factor 1.33 after 3 and 1.5 after five interventions (a), factor 1.2 after 3 and 1.33 after five interventions (b) and factor 1.2 after two and 1.33 after four interventions (c).

(a)

		Q_N			
		16.7% 0.362	50.0% 0.611	83.3% 1.083	
b	16.7% 0.089	0.65/0.87/0.98 60.59	1.55/2.07/2.33 52.93	1.35/1.80/2.03 54.15	opt. ILE SL
	50.0% 0.210	1.45/1.93/2.18 51.06	1.25/1.67/1.88 41.97	1.55/2.07/2.33 46.08	opt. ILE SL
	83.3% 0.478	1.05/1.40/1.56 35.74	1.15/1.53/1.73 40.19	1.65/2.20/2.48 43.59	opt. ILE SL

(b)

		Q_N			
		16.7% 0.362	50.0% 0.611	83.3% 1.083	
b	16.7% 0.089	1.65/1.98/2.20 61.55	1.65/1.98/2.20 59.1	1.35/1.62/1.80 47.78	opt. ILE SL
	50.0% 0.210	1.55/1.86/2.07 50.13	1.75/2.10/2.33 47.2	1.65/1.98/2.20 43.87	opt. ILE SL
	83.3% 0.478	1.65/1.98/2.20 41.64	1.05/1.26/1.40 37.74	1.75/2.10/2.33 39.02	opt. ILE SL

(c)

		Q_N			
		16.7% 0.362	50.0% 0.611	83.3% 1.083	
b	16.7% 0.089	0.65/0.78/0.87 55.39	1.45/1.74/1.93 53.44	1.35/1.62/1.80 48.79	opt. ILE SL
	50.0% 0.210	1.65/1.98/2.20 46.26	1.05/1.26/1.40 41.06	1.55/1.86/2.07 41.16	opt. ILE SL
	83.3% 0.478	1.55/1.86/2.07 40.58	1.65/1.98/2.20 42.19	1.55/1.86/2.07 41.51	opt. ILE SL

For tracks with good quality parameters, the variation of the input values leads to a deterioration regarding the reachable service life. Improvements can be found in some few cases for tracks with poor quality parameters. Here too, however, only results can be achieved which are also possible with the constant intervention level.

A small exception are tracks with a poor quality in Table 13 (a). In these two cases, it is possible to reach better results compared to the constant ILE. This is due to the fact that, at quite an early point in time, very high intervention levels are applied. For these values, no comparable reference cases exist for the constant ILE.

Furthermore, there is doubt as to whether such a low level of quality should be accepted during the whole service life. Hence, it would be more reasonable to use a constant intervention level for “poor tracks” in this case, too.

The executed sensitivity analyses show that the assumptions from the base scenario for the compliant intervention level lead to optimal results. This is true for tracks with good initial quality parameters, where it is reasonable to use a compliant ILE. Therefore, all further calculations based on a compliant intervention level are performed with one increase of the ILE after three tamping tasks by the factor of 1.33. However, also the variation of the parameters does not lead to a significant advantage of compliant intervention levels for “poor tracks”. Therefore, a higher constant ILE remains the best option for these tracks.

8.3.4 Summary

Based on the findings of the present chapter, some general conclusions can be drawn regarding the optimal intervention level and its consequences:

- Track quality itself is not an optimisation criterion but much more a fundamental input parameter. The initial quality Q_{N1} plays an elementary role.
- Track sections with poor quality should only be tamped when necessary – this describes a reactive maintenance regime together with a high constant intervention level. In this context, it is necessary to clarify: What is the worst acceptable track quality?
- Even in case of poor initial track quality parameters, it is possible to improve track quality significantly, but the effort is very high.
- For tracks with good track quality parameters a preventive maintenance regime based on a compliant intervention level is the most reasonable option. In these cases, the potential for optimisation is very high.
- The most important message is: Defining general tamping strategies is not a question of optimising track quality itself, the main challenge is to generate service life!

Besides the general findings, an algorithm is developed that makes it possible to find the optimal intervention level based on the given boundary conditions. This algorithm can be applied to any cross section in the network and is used for all further evaluations and analyses.

9

Optimal tamping schedule

The aspirations up to this point were related to finding a model for describing track quality, predicting tamping tasks in the future and finding an optimal intervention level. By dealing with these tasks, now it is possible to develop an ideal tamping strategy for any given boundary conditions. The challenging fact is that these analyses are carried out separately for each cross section. The boundary conditions of every cross section thus lead to its own results. Setting up a maintenance plan on this basis would lead to quite confusing outcomes. An example of this is shown in Figure 59.

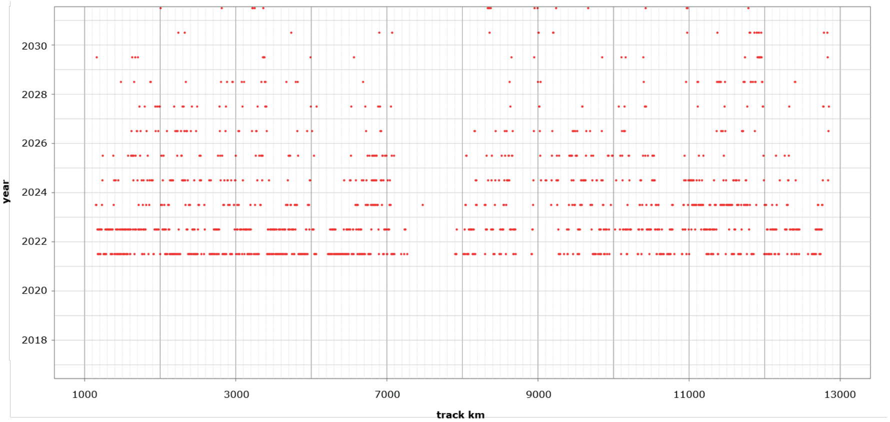


Figure 59: "Optimal" tamping schedule based on results for each cross section.

As the results in Figure 59 look like a random point cloud, this is not a sufficient basis for scheduling maintenance tasks for a linear asset like a railway track. Therefore, it is necessary to combine the results of each cross section to reasonable section lengths for tamping. This task is not an easy one, as a lot of boundary conditions have to be considered. The goal of the present chapter is to develop the algorithm *4tamp*^{ing} that automatically creates an optimal technical tamping schedule for the given boundary conditions. Thereby, the algorithm is based on the knowledge gained in the chapters before, and the optimal intervention level over the service life plays an elementary role. The entire algorithm is subdivided into several parts, whereby some parts are repeated in a loop, depending on the length of the observation period. In the following, the different parts of the algorithm *4tamp*^{ing} as well as their relations are explained in detail. However, the boundary conditions that must be considered are explained as a first step.

9.1 Boundary conditions

Before the development of an optimal tamping schedule, the technical boundary conditions of the considered section must be known or determined to define reasonable and executable section lengths. Some of these circumstances are predefined, and some of them can be defined by the user. The most important parameters that must be considered are:

- Technical constraint points
- Minimum working length
- Minimum gap

The main ideas behind these factors are explained briefly below.

9.1.1 Technical constraint points

By considering the longitudinal extension, the railway track is not a homogenous building. The continuous track is repeatedly interrupted by constraint points that affect the planning and execution of maintenance tasks like tamping. This is especially true for railway networks in topographically challenging areas like in Austria. As the present theses focuses on the planning of through-going tamping tasks for the open track, these points have to be identified and handled accordingly.

In this context, turnouts play an important role. Turnouts have to be considered as individual components, as they cannot be tamped with conventional line tamping machinery.

For tamping measures in turnouts, special turnout tamping machinery is used and the work is usually carried out independently from line tamping. It is not in the focus of the present thesis to plan tamping tasks for turnouts.

However, the location of turnouts must be considered, as they may interrupt line tamping tasks. Furthermore, it would not make sense to begin or end an intervention only a few meters before or after a turnout. Hence, they may represent logical beginnings and endings of line tamping actions.

Further engineering structures that must be considered by scheduling tamping tasks are bridges and tunnels. Same as for turnouts, also these buildings may represent a logical beginning or the end of an intervention. Though, regarding the interruption of a tamping task, there might be a difference. Bridges and tunnels only interrupt a tamping action if they are not constructed in the form of ballasted track. As many bridges and tunnels – especially shorter ones – are equipped with ballast bed, no interruption of a through-going task is intended due to them in the following.

Railway crossings are mostly equipped with removable plates that can be lifted away during the preparation works of a tamping action. Therefore, they do not influence a line tamping task and can be considered as open track. However, it would not be a problem to include railway crossings into the algorithm. In this case, they would have to be considered in the same way as bridges and tunnels.

9.1.2 Minimum working length

As already mentioned, the present thesis focuses on the planning of line tamping tasks for through-going actions. Hence, the repair of isolated defects on very short areas falls outside of the scope. For line tamping tasks, today normally modern high-performance machinery is used. These machines make it possible to tamp long, continuous sections in comparably short times. However, this also means that there must be correspondingly long sections in order to reap the advantages of such machines. In addition, there is also a technical reason that requires a minimum working length: At the beginning and at the end of every task, there must be generated a ramp that adapts the height of the tamped track to the surrounding sections continuously. The length of the ramp depends on the lift of the track during the tamping process and therefore the occurring difference in height. This means the minimum working length is not a fixed value, it much more depends on the machine used and the planned lift of the track. Therefore, the minimum work length is considered as a variable value that can be defined through the user.

9.1.3 Minimum gap

A tamping task means an intervention in the track system and especially the beginning and the ending of every maintenance action is a potential area for track failures [29]. Hence, it is desirable to have preferably long working sections to reach a continuous high track quality and to reduce potential failure areas. Furthermore, the workflow can be executed much more efficiently, as it can be performed continuously without any interruptions. To take account of these circumstances, a minimum gap that is acceptable between two tamping tasks must be defined. If the distance between two actions is lower than the minimum gap, the two interventions have to be combined into one continuous task. However, it must not be forgotten that tamping also contributes to ballast pollution. Therefore, tamping should be reduced to a minimum where it is not required. As the minimum gap depends on many factors, this value is also kept variable and can be defined by the user.

9.2 The algorithm *4tamp^{ing}*

As mentioned above, the algorithm *4tamp^{ing}* is developed that allows for the automatic creation of an optimal tamping schedule in a technical way. *4tamp^{ing}* is subdivided into different modules that are explained subsequently. Before the algorithm can start, some input parameters have to be defined. These parameters range from the considered track section to different values that are determined and described in the chapters before. The required input parameters together with example values are shown in Table 14. The different values are also explained at the point in the algorithm where they are needed.

Table 14: Example for input parameters for the algorithm *4tamp^{ing}*.

name	parameter
TUG number	8
track	1
km from [m]	171500
km to [m]	176000
year	2018
factor ILE	1.33
increase ILE	3
min. working length [m]	300
min. gap [m]	100
crit. tamping	0.50
# years	8

9.2.1 Module 1 – data preparation

The task of the first module of the algorithm *4tamp*^{ing} is the preparation of the data for further processing. The whole procedure is shown in Figure 60. Besides the input parameters, track geometry data (σ_{mod}) and the related time series with all available regression functions are imported. The latter data are required as the parameters from the most recent deterioration period must be known in the further modules. Furthermore, these data make it possible to start analyses in the past and compare the computed results with the actual behaviour. Additionally, asset data and all the data related to the model for calculating the cumulated traffic load are imported. After the import, a filter is applied to extract the data for the desired track section. Therefore, the line number, the track number and a start and an end kilometre are needed. These values are already defined in the input parameters by the user. In the present example, TUG line 8 on track 1 between km 171.500 and km 176.000 is regarded. Afterwards, the filtered data are merged together so that all required information is available for any cross section every 5 m. Within the last step, the prepared data are exported into a dedicated csv-file for further processing.

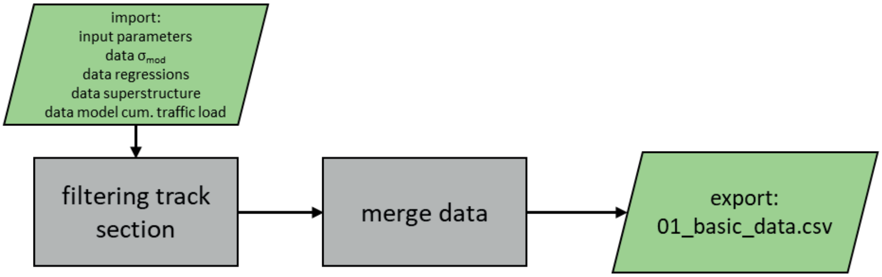


Figure 60: Flow chart module 1 - data preparation.

9.2.2 Module 2 – preparation for optimal intervention level

After preparing the required data, the next step is to assess the current track quality and determine the optimal intervention level for the current situation. As this is quite a complex task, the process is divided into two modules. The current module proceeds all necessary preparations and in module 3 (chapter 9.2.3), the optimal intervention level is calculated. In chapter 8, the optimal intervention level is defined as the value(s) that provide(s) the longest service life after ten tamping interventions. Therefore, the initial quality and the deterioration rate of the first deterioration period are required.

However, by planning tamping tasks for any section in the network, tracks of very different ages must be dealt with. Especially for older tracks, the track quality parameters of the first deterioration period and also the whole history of executed maintenance tasks are not available. Hence, the quality parameters of the current deterioration period are used, and the resulting service life for the next ten tamping tasks is utilised to determine the optimal intervention level.

The first step in module 2 is to import the input values, the prediction tables (Table 26 - Table 34) and the data of the desired section, prepared in module 1. The generated algorithm contains a loop that calculates the required information for every cross section (CS) sequentially. As a first step, it is checked whether at least one beginning of a deterioration period (DP) exists before the considered year (CY). The considered year is one part of the input values and must be defined by the user. Normally, when planning tamping tasks in the future, this would be the current year. However, it is also possible to choose dates in the past to compare computed results with actual values. This is a very good opportunity to validate the algorithm (chapter 10.2). When years are involved within the algorithm, the middle of the year is always considered. Afterwards, the date of the beginning of the most recent deterioration period (TB) is determined. If there is no value found for this, no further calculations and analyses are possible and only the failure values “NA” are output.

Afterwards, it is examined whether all preconditions and values for the application of the load model, described in chapter 7.3.1, are available. In this case, the cumulated traffic load (CL) at the beginning of the current deterioration period is calculated. Otherwise it would also be possible to determine the cumulated traffic load with a simplified model and the formula:

$$CL = LV * SL * 0.8 \tag{31}$$

CL	cumulated traffic load [gt]
LV	load value [gt/day]
SL	service life until the considered point in time [days]

This model provides a good estimation and considers the lower traffic loads in the past by using the factor of 0.8. A necessary precondition for applying the simplified model is that the track age is known. Otherwise, no calculations and further analyses are possible for this cross section.

In the next step, it is proven whether at least three measuring points are available between the beginning of the deterioration period and the current year. When this condition is fulfilled, it is possible to calculate a serious regression between TB and the current year.

Otherwise, it is not possible to apply a regression function. However, in this case, the values from the prediction tables can be used. As for their application the track quality and load values at the end of the last deterioration period (TL) are required, at least one past DP must be available. In the other case, no further analyses are possible for this cross section. In many cases, the end of the last (TL) and the beginning of the current deterioration period (TB) are equal. However, it does not always have to be that way, as there might be too few measuring points between two deterioration periods to calculate a regression. In this case, TL and TB are not equal and therefore an individual check and the separate calculation of TL is necessary. For the application of the prediction tables, the cumulated traffic load is a precondition. For their calculation, the same procedure is applied as described above. When all track quality (TQP) and load parameters from the last period are known, the prediction model can be applied and the track quality parameters for the current period can be calculated. If the given boundary conditions are not covered by the prediction tables, it is not possible to execute further analyses for this cross section.

By means of the linear regression or the parameters from the prediction tables, it is possible to determine the track quality for the next year (Q_{act}). This value is stored together with the track quality parameters of the current deterioration period. Afterwards, the algorithm continuous with the next cross section. The whole procedure of module 2 is depicted in Figure 61.

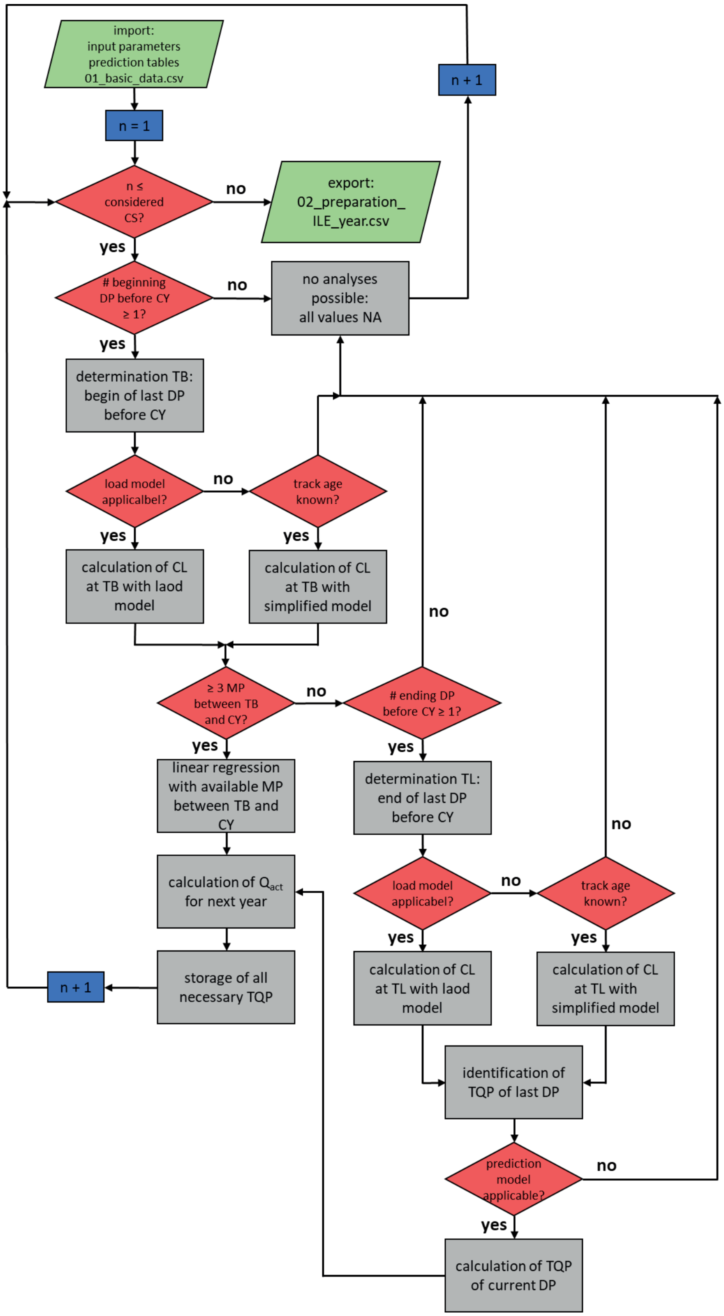


Figure 61: Flow chart module 2 – preparation for optimal intervention level.

9.2.3 Module 3 – optimal intervention level

After the preparations in module 2, now it is possible to calculate the optimal intervention level for every cross section based on its boundary conditions automatically. For the present module (Figure 62), in the first step, the input parameters, prediction tables, the basic data and the results of module 2 are imported. At first, constant intervention levels are investigated. Therefore, the required track geometry and load data are read from the considered cross section and stored in own variables. Furthermore, the intervention levels have to be defined that should be investigated. In the present case, the values range from 0.55 mm to 2.95 mm with an increment of 0.1 mm. Hence, for every cross section, 25 intervention levels are examined.

Afterwards, the time is calculated until the current intervention level is reached. For the first deterioration period, this is done by the track geometry parameters determined in module 2. For the further periods, the values come from the model basing on the prediction tables. Once the length of the current period is known, this value is added to the fictive service life (fSL) up to now. This service life must not be confused with the real service life. The fictive service life starts at zero at the beginning of the first deterioration period within the algorithm and increases subsequently by the length of the considered period (lDP). Furthermore, the cumulated traffic load at the end of the considered DP is calculated as input parameter for the prediction model. Next, the algorithm tests whether the model based on the prediction tables is applicable for the given boundary conditions. This includes in particular the check whether the current track quality (Q_{act} for the first deterioration period and afterwards Q_N) lies under the currently considered ILE. If the check is negative even for one of the ten deterioration periods, no result can be generated for the present intervention level and failure values are output. Otherwise, the algorithm calculates the track geometry parameters for the next period and the loop starts again until ten deterioration periods are treated. As a result, the fictive service life after ten DP reached with the considered intervention level is stored. This procedure is repeated until all 25 ILE are tested.

After testing the constant intervention levels, in the next step the compliant intervention levels are examined. Therefore, the required track geometry and load data are once again read from the considered cross section and stored in own variables. Also, in this case, 25 different combinations of ILE are investigated. Just as for the constant ILE, values from 0.55 mm to 2.95 mm are tested. These values represent the lower ILE for the first three interventions. After three tamping tasks, the considered ILE is increased by the factor of 1.33. These values were determined in chapter 8.3.

For testing the consequences of the ILE, the same procedure is executed as before. In the end, for the 25 ILE-combinations, the related fictive service life after ten deterioration periods is stored as a result.

By merging the results of the constant and compliant ILE, for all tested intervention levels, the resulting fictive service lives are available. In the last step, the optimal ILE is determined by choosing the value(s) that provide(s) the longest fictive service life. Thus, it is also automatically defined whether a constant or a compliant ILE should be applied. The whole procedure is repeated for every CS in the considered track section.

This algorithm allows for the detection of the optimal intervention level for tracks during the service life. However, it is also possible to define the tamping strategy for a new track once the track geometry parameters of the first deterioration period are known.

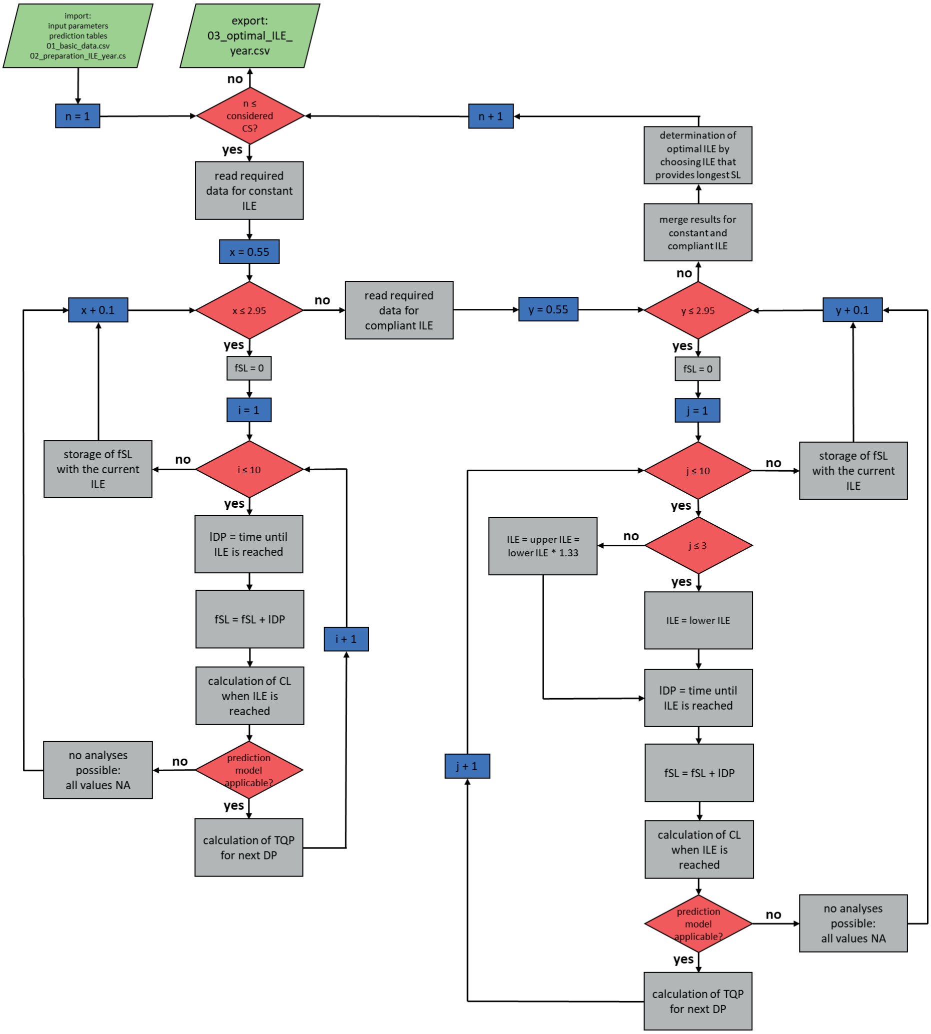


Figure 62: Flow chart module 3 – optimal intervention level.

9.2.4 Module 4 – optimal point in time for tamping

At this stage, the optimal intervention level for the next tamping task(s) is known. The function of the present module (Figure 63) is now to calculate the point in time at which this ILE is reached and therefore an intervention should be carried out.

The first step is to import the input parameters together with the files containing the results of the first three modules. One of the first tasks of the present algorithm is to check whether it was possible to determine an optimal intervention level for the considered cross section in module 3. If so, it is possible to calculate the point in time when this intervention level is reached (OPiT). Therefore, the track geometry parameters determined in module 2 are used together with the linear regression function. If it was not possible to determine the optimal intervention level, it might be feasible to apply a simplified model regarding Auer [104] (see also chapter 5.6) to calculate an intervention level. As this model distinguishes between younger and older tracks, a threshold value of 180 million gt is defined. Tracks that exceed this cumulated load can be regarded as older tracks and sections with a lower cumulated traffic load as younger tracks. However, this means it must have been possible to calculate a cumulated traffic load in the previous modules. Otherwise, no further analyses are possible and failure values are output. After calculating the ILE, it must be checked if the current track quality (Q_{act}) is lower than the intervention level. In this case, it is also possible to make a linear regression to determine the point in time reaching the ILE (PiT). If Q_{act} already exceeds the ILE, a tamping task is planned for the next year. This is done because the tamping schedule is intended to consider a mid-term planning horizon. Therefore, it always starts one year after the current year defined in the input parameters. Furthermore, an intervention in the present year would be too short-term.

In the event of executing regressions, it is possible to calculate the ideal point in time for the tamping intervention accurate to the day. For planning tamping tasks, it would not make sense to work on such a detailed base as the tamping machines are only available for a certain area one or a few times a year. Anything else would not make economic sense either. This means all tamping tasks within a certain area have to be bundled. This is done by assigning the results to one year where tamping should be executed. When doing so, one circumstance must be considered: In Austria, it is not possible to execute tamping tasks throughout the entire year due to frost in the winter time. Therefore, it is assumed that tamping tasks can start on 1 April, which is designated as the beginning of the tamping year. If the optimal point in time for tamping lies before this date, the task is brought forward to the previous year. Otherwise, the task is planned for the calculated year. For example, a task that should be executed on 3 February 2021 is accordingly scheduled already for 2020. In contrast, a measure that should be done on 5 July 2021 is scheduled for 2021.

After determining the year in which the next tamping task should be executed, the algorithm starts with the calculations in the next cross section.

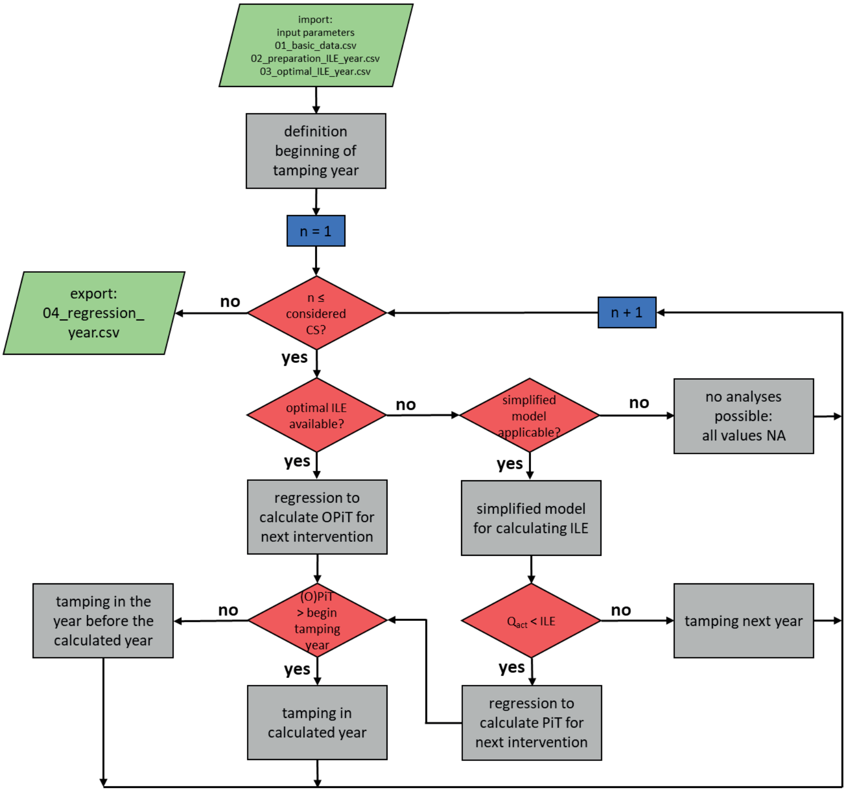


Figure 63: Flow chart module 4 – optimal point in time for tamping.

9.2.5 Module 5 – tamping sections

After calculating the ideal point in time for tamping in every cross section in module 4, the task of module 5 (Figure 68) is to combine all the results to reasonable section lengths for tamping. This is done on the basis of the boundary conditions introduced in chapter 9.1. As a first step, the input data and the results from the regression are read in. Afterwards, the considered section (defined in the input data) is divided in sub-sections based on constraint points that interrupt a continuous tamping task. As explained in chapter 9.1, turnouts are considered as such points. Figure 64 gives an example of this procedure. As there are two turnouts (brown dots) within the considered section reaching from point A to point B, the area is divided into three separate sub-sections marked in red. Afterwards, every sub-section is dealt with separately.

The length of one sub-section must be longer than the minimum section length as otherwise no further calculation is possible. This case might only occur in short track sections within turnout areas. As these areas are tamped together with the turnout, they are outside of the scope of the present thesis. The blue dot represents a bridge and does not lead to the creation of an own sub-section.

Figure 64: Dividing a section into sub-sections.

In the next step, the currently considered sub-section is divided into segments with the minimum working length (MWL). This length can be defined within the input parameters and comprises a length of 300 m in the present example. The segmentation is executed in a sliding way, as this has a lot of advantages compared to fixed sections (chapters 4.4, 5.5). As a step size for the calculation, five meters is used, as all required data are available every five meters within the data base (chapter 6.3.1). Next, it must be decided if a section should be tamped in the considered year or not. This is not an easy decision, as the calculated years within the regressions in module 4 is the optimal point in time for tamping. However, this also means that sections that are intended to be tamped later or earlier but are co-treated in the considered year, are not dealt with optimally. For example, it will not make sense to tamp a section of 300 m only because of one cross section that reaches its optimal point in time in the considered year. This would lead to disadvantages for all the other cross sections. Therefore, for every segment, it is checked whether the “tamping criteria” is fulfilled. The tamping criteria means that a certain percentage of cross sections reach their ideal point in time for tamping in the related year. The percentage can also be defined within the input data. However, a value of 50 % is recommended and used as this guarantees an optimal decision at least for more than 50 % of the section. If the percentage is exceeded, the section is intended to be tamped in the considered year and the detailed kilometres of the concerned cross sections are stored. Otherwise, no tamping is planned in the section within this step.

At this stage, the algorithm has detected all segments that should be tamped in the considered year. As they have all the same length of 300 m and are overlapping, the sections are assembled to continuous tamping lengths (CTL). The advantage of this methodology is that all CTL already have the length of at least the MWL.

The process of segmentation and determination of continuous tamping lengths is shown as an example in Figure 65 for sub-segment 2. The segmentation process starts at the first turnout (seg. 1) and is repeated until the end of the sub-section (seg. n).

In the example the first three segments are considered. The first two fulfil the tamping criteria, the third not. This means the first continuous tamping length (CTL_1) starts at the beginning of the first segment and ends at the end of the second segment. By repeating this procedure until the end of the sub-section, it turns out that there are two further continuous tamping lengths (CTL_2, CTL_3) – both of them have the minimum working length.

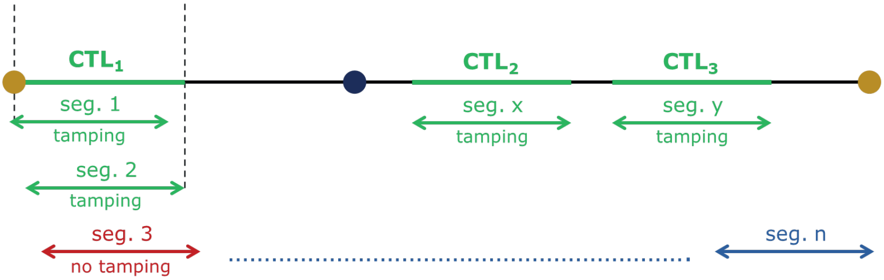


Figure 65: Segmentation and determination of continuous tamping lengths.

In the next step, it must be checked whether there are any gaps between a tamping task and a constraint point (CP) that is lower than the minimum gap (MG). In the present example, the gap between CTL_1 and the bridge as well as from CTL_3 to the turnout is wider than the MG. In contrast, the gap between the bridge and CTL_2 is shorter than MG. Therefore, the task is extended until the bridge, which is the new starting point of CTL_2. This is depicted in Figure 66. By extending a measure until a constraint point, it must be checked whether there is any other task nearer than the constraint point. In this case, the extension would be executed until the beginning/end of the measure and not until the constraint point to avoid any overlapping. After this step, it might be the case that there are some tasks that abut directly. In this case, the two tasks are merged to one continuous measure. In the present example, this possibility does not exist.

Figure 66: Checking the gaps to constraint points and between two tasks.

Within the last step, the gaps between two tasks are checked regarding the minimum gap (Figure 66). If the gap falls below the value of the minimum gap, the two tamping lengths are merged together to one CTL. In the present example, the gap between CTL_2 and CTL_3 is too short. Therefore, the two lengths are combined to one section. The final result for the continuous tamping lengths is shown in Figure 67.

Figure 67: Final result for continuous tamping lengths.

After the continuous tamping lengths for one sub-section are determined, the procedure is repeated for the next one(s). In the end, the results and therefore the CTL for every sub-section are stored in an export file.

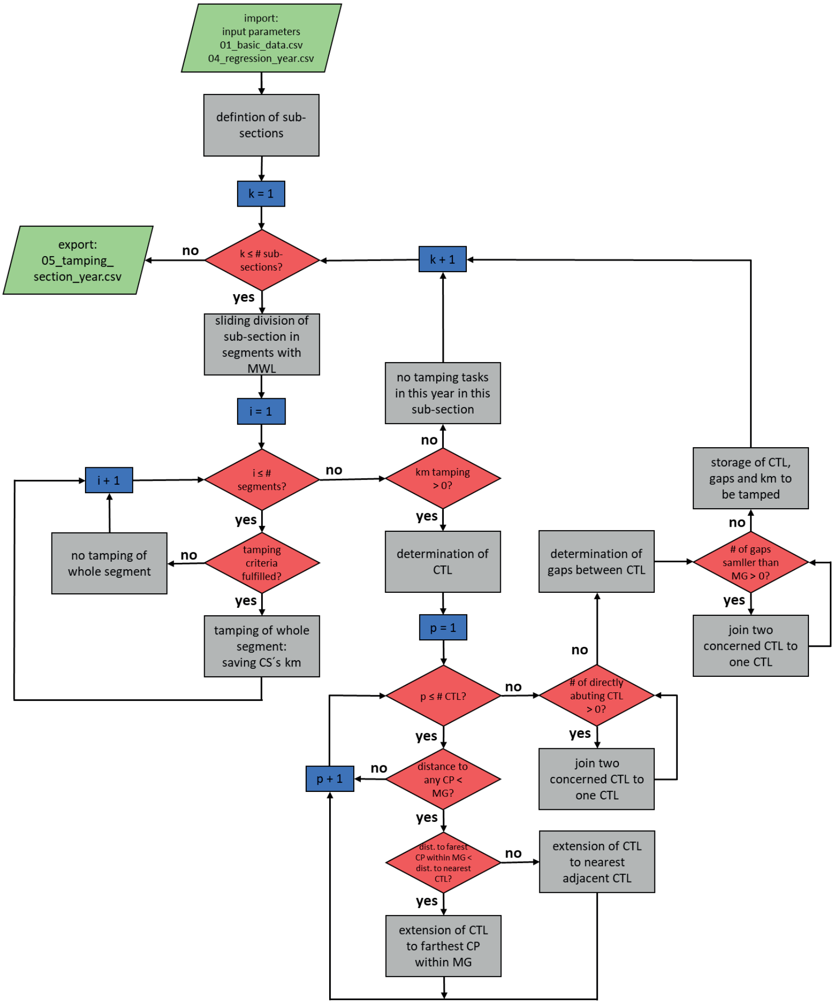


Figure 68: Flow chart module 5 – tamping sections.

9.2.6 Module 6 – preparation of data for the next year

The tamping schedule should not only be created for one period but also for the upcoming years. Therefore, the consequences of executing a tamping task or the non-execution have to be considered. This especially concerns the optimal intervention level that has to be calculated for the new circumstances.

Hence, there are different cases that have to be distinguished requiring different measures in data preparation for the further consideration:

- CS that are tamped at the ideal point in time: For these cross sections, the optimal intervention level and therefore the ideal strategy is applied. To distinguish between the first and the second value of the compliant ILE, the optimal intervention level for the next intervention must be identified. Furthermore, the new track quality parameters after the intervention have to be determined.
- CS that are tamped but not at the ideal point in time: These cross sections are tamped although it is not necessary yet regarding the optimal intervention level. This happens in case of co-treating CS to reach the minimum working length or to close too short gaps. This means the intervention is too early, and the optimal strategy was not applied for these CS. This situation changes the circumstances and might have influence on the next optimal intervention level. Therefore, the optimal ILE has to be recalculated. Also, the new track quality parameters after the intervention must be estimated.
- CS that are not tamped although the ideal point in time was reached: This case occurs if there are cross sections that have their ideal point in time for tamping in the considered year, but the tamping criteria in the related segments is not fulfilled. Also, for these CS, the ideal strategy is not applied which might have consequences on the optimal ILE. Therefore, a recalculation of the optimal intervention level is necessary.
- CS that are not tamped and have their ideal point in time in the future: For these CS, no tamping task is executed in the considered year and it is not necessary. In this case everything was done right, and no recalculation of the optimal ILE is necessary.

The preparation of the data for a possible recalculation of the optimal intervention level is the task of module 6 (Figure 69). At first, all required data are imported, and the considered year is increased by one. Next, the cross sections, tamped in the year under consideration, are filtered. For these cross sections it is necessary to determine the new track quality parameters after tamping based on the prediction model. The prerequisites for this are to know the cumulated traffic load when tamping is executed (based on the load model if possible, otherwise due to the simplified model) and the applicability of the model.

If it is possible to use the prediction model based on the prediction tables, the track quality for the next year (Q_{act}) can also be calculated. Afterwards, all required track quality parameters for the current cross section are stored and the procedure is repeated for all tamped CS.

Subsequently, all cross sections that were not tamped are filtered, although their optimal point in time lay in the considered year. For these CS, the initial quality and the deterioration rate remain the same, only the track quality for the next year (Q_{act}) must be calculated. Afterwards the parameters are stored, and the procedure is repeated for all concerned cross sections. Within the last step, the required data are stored for all CS where a recalculation of the optimal ILE is necessary.

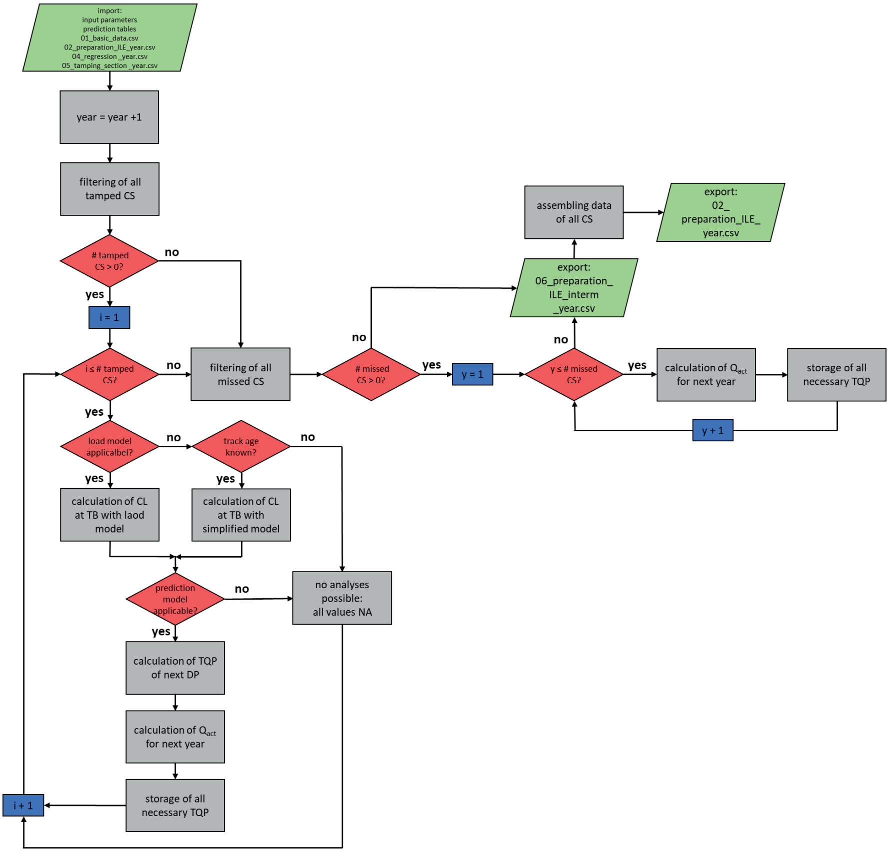


Figure 69: Flow chart module 6 – preparation of data for the next year.

9.2.7 Module 7 and 8 – optimal ILE and regression for the next year

Based on the prepared data from module 6, in module 7 and 8, the optimal intervention level and the regressions are recalculated for cross sections where this is necessary.

As the methodology is completely the same as in module 3 and 4, no separate flow charts are depicted. The only difference is that the procedures are not executed for all cross sections but only for those where a recalculation is required. Therefore, two export files are generated, one with only the handled cross sections, and one where the handled cross sections are combined with the residual cross sections and their results.

9.3 Summary of the algorithm *4tamp*^{ing}

By combining the modules described in chapter 9.2, an optimal tamping schedule for the upcoming years can be created based on the boundary conditions in chapter 9.1. Figure 70 gives an overview of the whole algorithm *4tamp*^{ing} and the interconnection between the different modules. In any case, the modules 1 to 5 must be executed to subsequently create a tamping schedule for one year. If more upcoming years should be covered by the schedule, also the modules 6 to 8 have to be proceeded. After module 8, module 5 is executed again to create continuous tamping lengths. The modules 5 to 8 are repeated in a loop until the last year of consideration is treated. The number of years that should be dealt with can be defined within the input parameters. After all relevant years are considered, and the related continuous tamping tasks are stored, the algorithm stops and the tamping schedule is exported in a graphical image. The coordination of the different modules is thereby done by a separate control code. Overall, for generating the tamping schedule, it is necessary to define the input parameters and to run the control code, nothing more. All the other steps are processed automatically by the different modules and their interconnections.

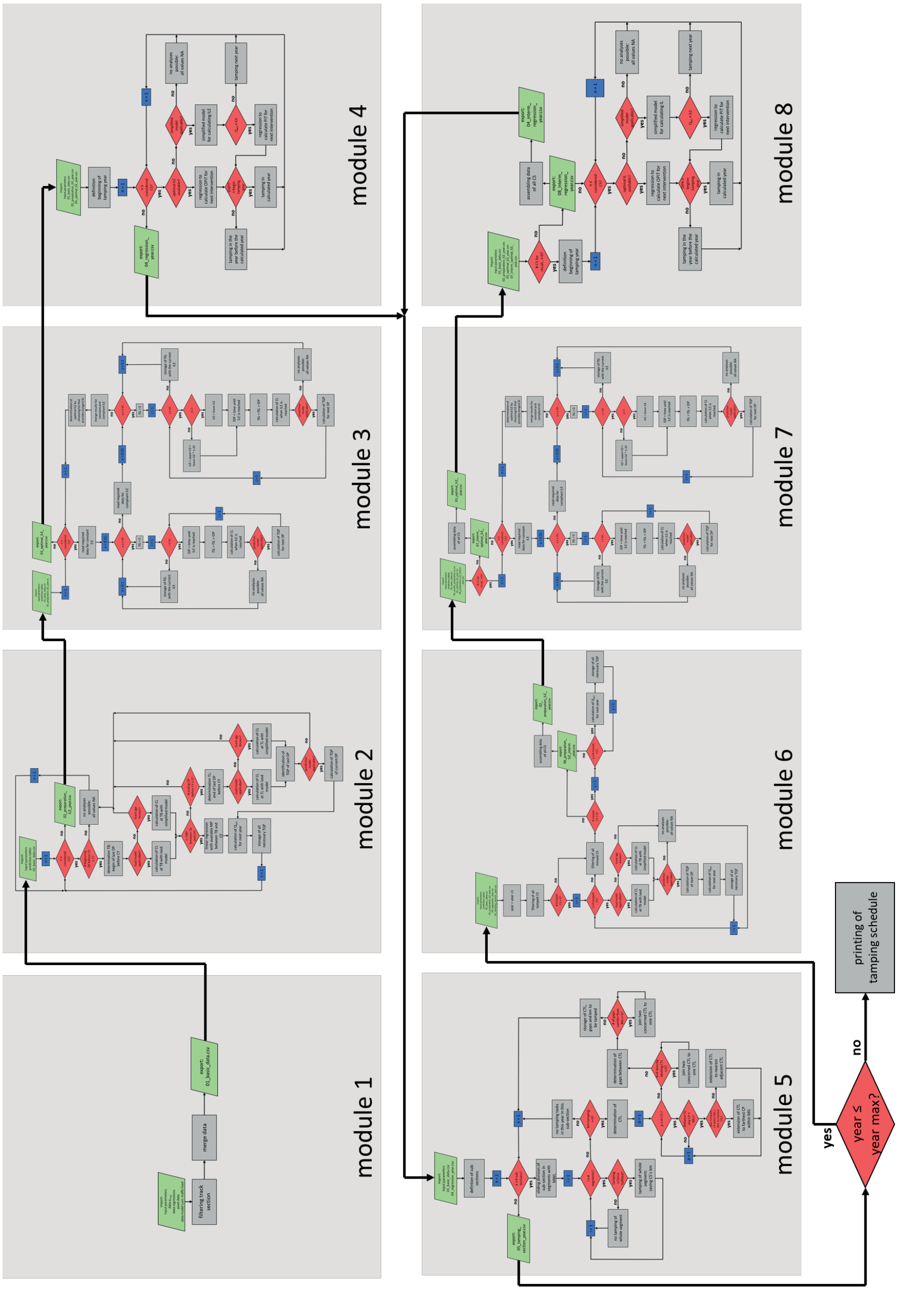


Figure 70: Overall algorithm *4tamp*^{ing} to creating an optimal tamping schedule.

10

Application of the algorithm *4tamp*^{ing}

After the description of the whole procedure for creating optimal tamping schedules, the algorithm *4tamp*^{ing} is applied in this chapter. Therefore, three sections are chosen, and tamping schedules are created. In a subsequent step, the developed schedule is compared with actually performed tamping actions in reality. In addition to the comparison, the question arises as to whether the application of the optimised schedule could have led to better results than the strategy applied in reality. To answer this question, a comprehensive validation process is executed. In the last step, the economic consequences of potential improvements in tamping scheduling are analysed.

10.1 Application on test sections

For applying the algorithm *4tamp*^{ing}, three test sections on a railway line in Austria (designation within the database: TUG 8) are selected. By choosing the sections, importance is attached to find longer continuous areas with homogenous asset properties. This is done to create comparable results on the whole section. As it is the goal to compare the results also with actually executed tasks, the tamping schedule is not created from now on into the future but starts in 2010 and contains a time span of nine years. Therefore, the following three sections are selected:

- The first section is located between km 49.000 and km 55.000. The section is equipped with concrete sleepers and was installed between 1993 and 1997. Within this area, three turnouts and four bridges are located.

- The second section lies between km 171.500 and km 176.000. In this section, concrete sleepers were installed in 1994. The whole area contains three bridges. This section is chosen as it shows quite similar properties as the first section and therefore provides the possibility for comparisons in the results.
- Besides the two sections above already exhibiting a notable track age, a section is also selected where quite a new track is installed. This section is located between km 16.000 and km 23.7000 and is mainly equipped with concrete sleepers with under sleeper pads from the year 2009. Therefore, tamping actions in the year 2010 have to be considered as “stabilisation tamping” to correct initial settlements after replacement. These tasks cannot be seen as maintenance tasks but much more as part of the renewal. As the renewal works are not in focus of the present thesis, “stabilisation tamping” is not covered by the resulting tamping schedule either. Therefore, the predicted tamping tasks start in the year 2011 instead of 2010 in this case. The considered area contains 18 bridges and two turnouts.

As the planning horizon between 2010 and 2018 is analysed, the first two sections exhibit a track age of about 15 years at the start of the tamping schedule. In contrast, the third section contains a track at the very beginning of its service life, and, therefore, the first years of the life cycle are covered by the schedule. The resulting tamping schedules are depicted in Figure 71, Figure 72 and Figure 73.

For the section between km 49.000 and km 55.000 the tamping schedule in Figure 71 indicates tamping tasks in every year. The maintenance plan shows rather short tasks that are distributed over the whole section. Particularly noteworthy is the area after the turnouts between km 51.400 and km 51.850, where five tamping tasks are scheduled in the first six years of the planning horizon. Afterwards, no further tasks are indicated. This suggests very poor track quality parameters in this area and that a correction by means of a high tamping effort is the best strategy.

Also, the tamping schedule in Figure 72 for the track section between km 171.500 and km 176.000 proposes tamping actions every year. In contrast to the previous sections, the tasks are more continuous and therefore longer. Furthermore, the general tamping interval is higher compared to the section before. Particularly noteworthy is the area from km 173.500 to the end as there are nearly continuous tasks proposed in the first three years and afterwards every two years. This is an indicator for very poor quality parameters that should be improved by means of tamping tasks to generate the longest possible service life.

As expected, a completely different result is achieved in the third section between km 16.000 and km 23.700. As depicted in Figure 73, only a few tamping tasks are proposed for the considered years. That is not surprising, as the whole section stands at the very beginning of its service life. As the section is equipped with under sleeper pads, quite a high initial quality together with a low deterioration rate can be assumed, leading to significantly stretched tamping intervals [11]. This fact is exactly what finds expression in the resulting tamping schedule.

Figure 71: Optimised schedule *4tamp*^{ing}: km 49.000 – km 55.000.

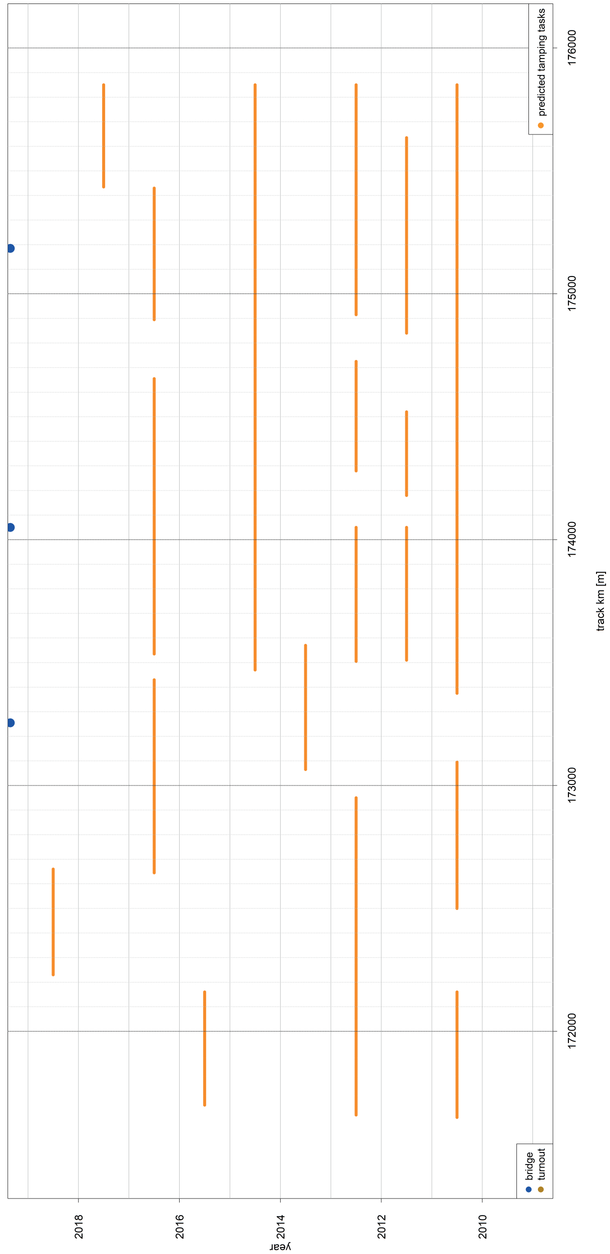


Figure 72: Optimised schedule *4tamp*^{ing}: km 171.500 – km 176.000.

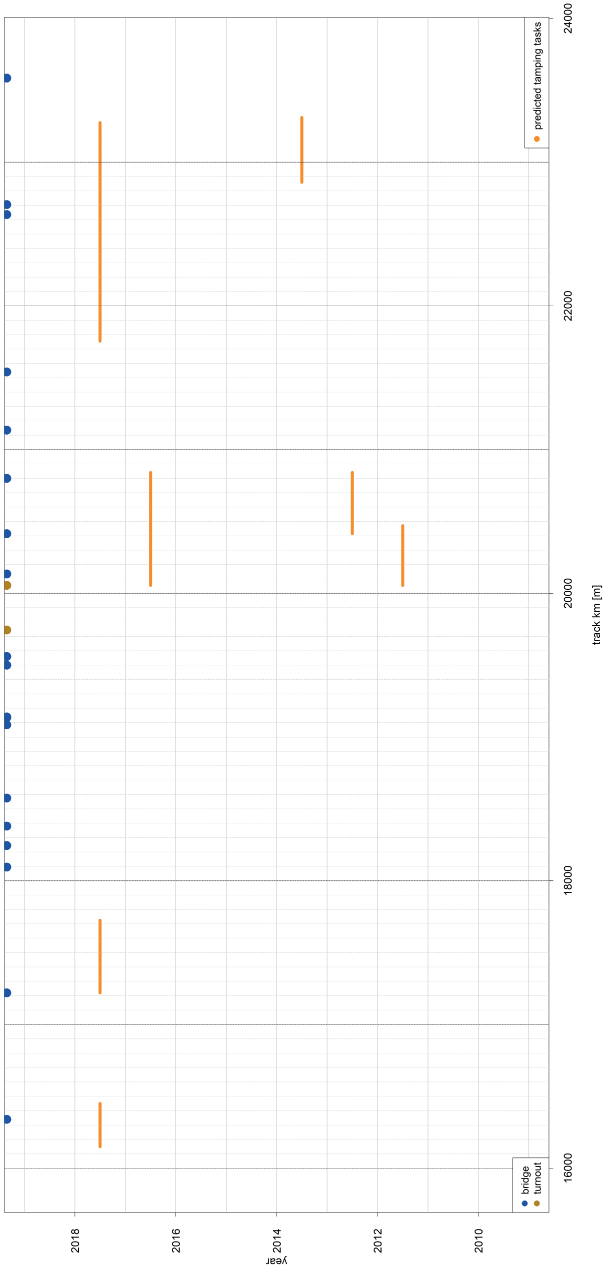


Figure 73: Optimised schedule *4tamp*^{ing}: km 16.000 – km 23.700.

10.2 Validation of optimal tamping schedules on test sections

The possibility of setting up the tamping schedule for any desired year provides the option of comparing the predicted tasks with the actually executed ones. This comparison is described in the following sub-chapters for every test section. Furthermore, it is possible to compare the resulting track quality parameters and the service life with the values that would be derived from the actually executed tamping strategy. To estimate the required values which would result from the actually executed strategy, a dedicated set of algorithms is created. These algorithms apply the same methodology as for the predicted tamping tasks basing on the prediction tables. The algorithms start at the last actually executed task and repeat the prediction methodology until ten tamping tasks are reached in total. Thereby, the already executed tasks from the year of consideration are taken into account. For example, when already three tasks were executed, the algorithm is proceeded for the next seven tasks. As the intervention level in the future is unknown, the averaged ILE of the last task is used for the upcoming actions. If this level is already exceeded, the next intervention is planned immediately. In the end, the algorithms store all relevant track quality parameters together with the resulting service life for every cross section enabling the comparison. As a lot of boundary conditions influence the actually executed tamping tasks, it is to be expected that, in the past, the strategy applied was not the very best in any case. Therefore, the present validation process cannot provide the information if the results from the developed model are “right” or “wrong”. Rather it should show the possible potential for optimising the tamping schedule based on the before discussed boundary conditions.

10.2.1 Section 1

Figure 74 shows the actually executed and the predicted tamping tasks for the section between km 49.000 and km 55.000. Table 15 illustrates in detail the length of the tasks in every year together with the summarised values. The results show that in reality about twice as many measures have been executed as the optimal plan would suggest. In reality, an average tamping interval of about 2.5 years was executed and the optimal schedule would lead to a tamping interval of five years for the observed nine years. Furthermore, it is striking that the actually performed tasks exhibit significantly longer continuous lengths.

Table 15: Summary of actually executed and predicted tamping tasks: km 49.000 – km 55.000.

	actually executed		predicted	
	CS	meter	CS	meter
2010	0	0	245	1225
2011	890	4450	80	400
2012	24	120	528	2640
2013	626	3130	192	960
2014	40	200	261	1305
2015	880	4400	331	1655
2016	806	4030	183	915
2017	544	2720	199	995
2018	579	2895	145	725
total	**4389**	**21945**	**2164**	**10820**
meter/year	**2438**		**1202**	
interval	**2.46**		**4.99**	

In Table 16, the resulting track quality parameters and service lives for the two cases are shown. These values are always the medians of the specific parameter over the whole section. It becomes apparent that the predicted schedule based on the optimal ILE leads to poorer values for the initial quality, the deterioration rate and also for the quality before tamping (equals a higher intervention level). These values are always true for the last deterioration period before, in total, ten tamping actions are reached. However, in contrast to the track quality parameters, it is possible to reach a significant improvement in the reachable service life. With the optimised schedule, about 39 years and, using the actual strategy, about 24 years can be achieved until ten tasks are executed (starting from 2009). This result equals an improvement of 59 % on average by applying the optimised schedule for the considered section.

Table 16: Resulting parameters for actually executed and predicted tamping tasks: km 49.000 – km 55.000.

	actually executed	predicted
Q_N [mm]	0.79	0.90
b [mm/y]	0.21	0.28
Q_{ULT} [mm]	1.28	1.80
service life [y]	24.16	39.27

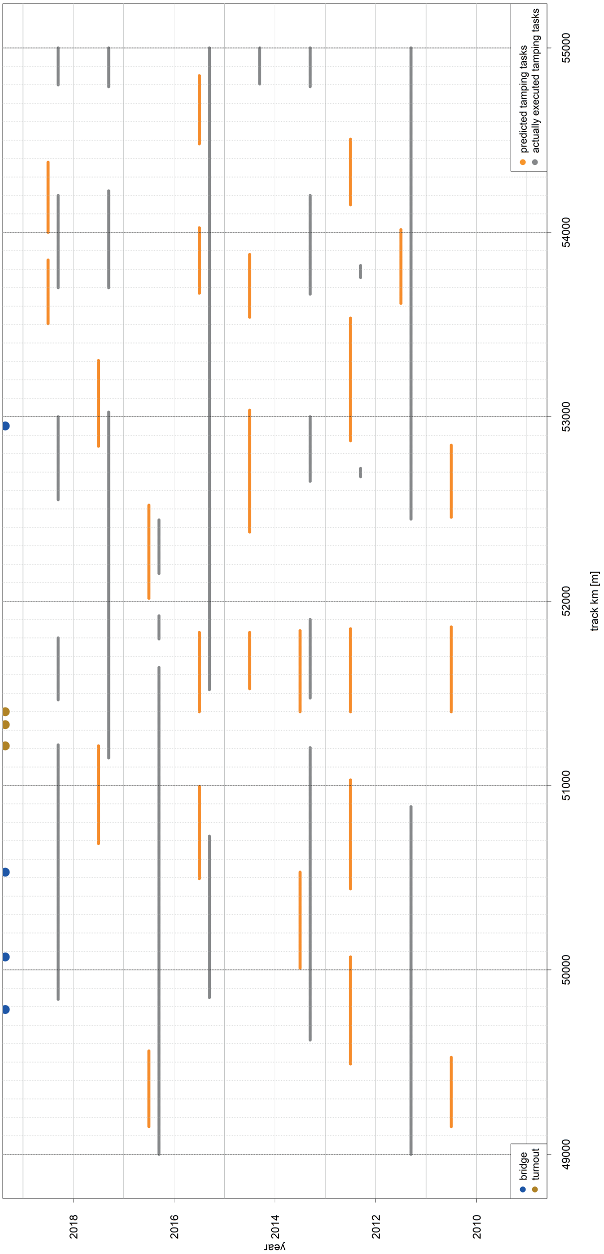


Figure 74: Optimised vs. actually executed tamping schedule km 49.000 – km 55.000.

10.2.2 Section 2

Figure 75 shows a comparison of the predicted and the actually executed tamping schedule between km 171.500 and km 176.000. Besides the optical evaluation, the detailed list with the tamping amounts in Table 17 shows more tamping tasks in the prediction than in reality. In reality, a tamping interval of about four years is executed. However, the prediction based on the optimised ILE shows a tamping interval of about 2.7 years. This means, the tamping effort is about one third higher in the prediction than in reality. In contrast to section one, the tasks predicted for the present section are much longer and more continuous.

Table 17: Summary of actually executed and predicted tamping tasks:
km 171.500 – km 176.000.

	actually executed		predicted	
	CS	meter	CS	meter
2010	408	2040	716	3580
2011	602	3010	335	1675
2012	1	5	643	3215
2013	0	0	101	505
2014	285	1425	476	2380
2015	588	2940	92	460
2016	44	220	488	2440
2017	107	535	83	415
2018	0	0	86	430
total	**2035**	**10175**	**3020**	**15100**
meter/year	**1131**		**1678**	
interval	**3.98**		**2.68**	

Table 18 shows the relevant averaged track quality parameters and the achievable service life for the two compared strategies. The results indicate a slightly poorer initial quality for the predicted actions and an equal deterioration rate after ten deterioration periods. The quality before tamping is better for the actually executed tamping tasks again. In contrast, the service life for the predicted tasks based on the optimal ILE is higher than for the actually executed ones. In total, an increase in service life of 13 % can be achieved by applying the developed methodology for this section.

Table 18: Resulting parameters for actually executed and predicted tamping tasks:
km 171.500 – km 176.000.

	actually executed	predicted
Q_N [mm]	0.87	0.91
b [mm/y]	0.28	0.28
Q_{ULT} [mm]	1.59	1.80
service life [y]	30.80	34.92

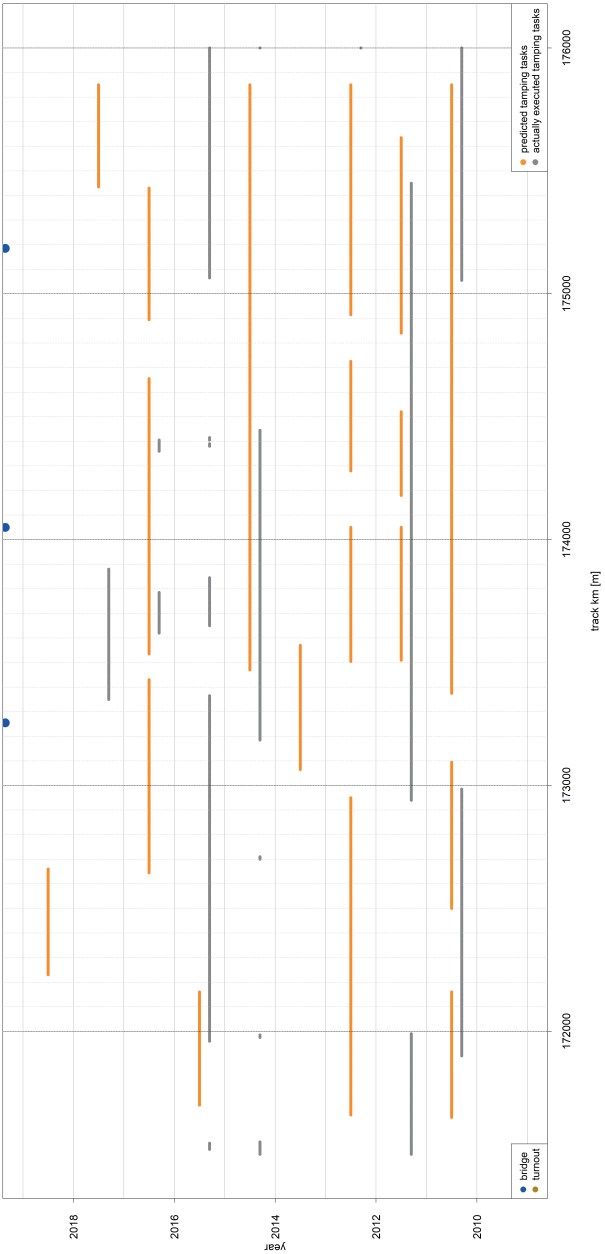
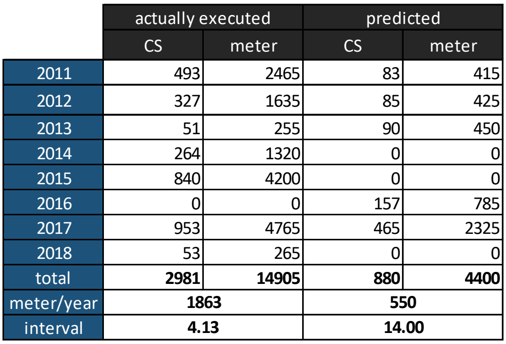


Figure 75: Optimised vs. actually executed tamping schedule km 171.500 – km 176.000.

10.2.3 Section 3

Figure 76 shows a comparison of the predicted and the actually executed tamping schedule for the section between km 16.000 and km 23.700. The detailed results per year together with a summary are depicted in Table 19. The results demonstrate that in reality considerably more tamping actions are executed compared to the prediction based on the optimal ILE. While in reality a tamping interval of about four years is executed on average, the tamping interval in the prediction is higher by a factor of 3.5. A very interesting section in this context is the area between km 18.200 and km 19.000. After stabilisation tamping in 2010, three more tamping tasks were executed in the following five years. This is a very dense interval and should normally not be necessary for a new track equipped with USP. Detailed evaluations for this section are carried out in chapter 10.3.

Table 19: Summary of actually executed and predicted tamping tasks: km 16.000 – km 23.700.



	actually executed		predicted	
	CS	meter	CS	meter
2011	493	2465	83	415
2012	327	1635	85	425
2013	51	255	90	450
2014	264	1320	0	0
2015	840	4200	0	0
2016	0	0	157	785
2017	953	4765	465	2325
2018	53	265	0	0
total	**2981**	**14905**	**880**	**4400**
meter/year	**1863**		**550**	
interval	**4.13**		**14.00**	

Table 20 shows the relevant averaged track quality parameters and the achievable service life for the two cases. The results indicate poorer values for the initial quality, the deterioration rate and also for the quality before tamping. However, as this is a new section, the ILE with 1.40 mm is lower as in the two sections before, where the ILE was about 1.80 mm. In contrast, the service life for the predicted tasks based on the optimal ILE is significantly higher than for the actually executed ones. In total, the achievable service life can be increased by 35 % by applying the developed methodology for this section.

Table 20: Resulting parameters for actually executed and predicted tamping tasks: km 16.000 – km 23.700.

	actually executed	predicted
Q_N [mm]	0.57	0.82
b [mm/y]	0.17	0.23
Q_{ULT} [mm]	1.04	1.40
service life [y]	38.64	48.86

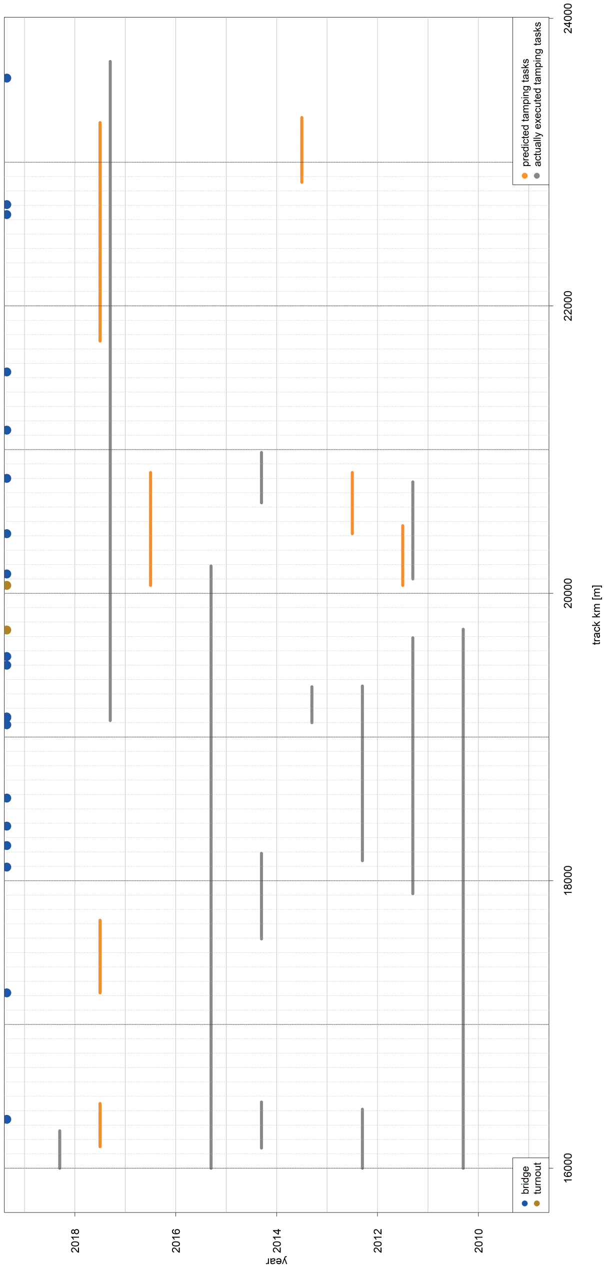


Figure 76: Optimised vs. actually executed tamping schedule km 16.000 – km 23.700.

10.2.4 Summary of the validation process on test sections

The results of the comparisons in the different test sections show a clear result. For the optimised tamping schedule, in nearly every case, poorer track quality parameters are indicated for the last of the ten observed deterioration periods. In contrast, when applying the developed algorithm *4tamp^{ing}*, the time it takes to reach ten tamping tasks can be stretched significantly. This means it is possible to prolong the service life considerably in any of the three test sections. As the average values for all three sections in Table 21 show, it is possible to stretch the service life by 32 %. Once again, these results clearly point out that an optimisation regarding track quality is not the right strategy. It is much more important to take care of the reachable service life and to apply a strategy that optimises this parameter. Furthermore, the summary in Table 21 depicts that the stretched service life is reached with a lower tamping effort in the considered time span of nine years. Although section 2 requires more tamping tasks as in reality, tamping intervals are stretched by 59 % for all three sections in the considered period.

Table 21: Summary of the comparison between actually executed and predicted tamping tasks.

	tamping interval [y]	service life [y]
executed	3.37	31.9
predicted	5.35	42.3
deviation	**59%**	**32%**

10.3 Punctual validation for short sections

The comparison of actually executed and predicted tamping tasks provides another very good possibility to validate the developed model. In sections where executed and predicted tasks are overlapping in one year, it is possible to compare the resulting track quality parameters in the next deterioration period. This comparison can only be executed when the first real and the first predicted task of the plan are scheduled in the same year. Otherwise, different ILE would be used, making a reliable comparison impossible. Therefore, for every test section, some short areas are chosen where the preconditions are fulfilled to validate the prediction model.

In Table 22, the results of the punctual validation process are shown. For the two track quality parameters Q_N and b, the differences between the predicted and the real values are calculated in every cross section. Afterwards, the median of the differences is determined and indicated in Table 22.

To test the statistical significance of the deviations, additionally, correlation analyses are carried out. As the data sets do not exhibit a normal distribution, the same methodology as in chapter 7.3.2 is used.

This means the correlation coefficient ρ_{SP} (Spearman's rho) is calculated and to test whether a statistically significant correlation exists, the probability value (p-value) is determined. These values are also shown in Table 22 for every examined case. If there is a statistically significant correlation between the data sets of the predicted and the real parameters, it can be assumed that the prediction model delivers results with sufficient accuracy. Compared to mean value tests, the correlation analysis brings the advantage of considering the differences in every cross section directly and not only in the mean values of the whole data sets.

Table 22: Summary of the punctual validation process.

	Q_N		b	
	diff [mm]	spearman ρ (p-value)	diff [mm/y]	spearman ρ (p-value)
section 1: km 53.615 - km 54.015	0.022	0.712 $2.2 * 10^{-16}$	-0.003	0.708 $2.2 * 10^{-16}$
section 2: km 171.900 - km 172.160	0.022	0.759 $8.6 * 10^{-8}$	0.024	0.763 $7.4 * 10^{-8}$
section 2: km 172.500 - km 172.985	0.044	0.697 $2.2 * 10^{-16}$	-0.069	0.819 $2.2 * 10^{-16}$
section 2: km 175.055 - km 175.850	-0.111	0.651 $2.2 * 10^{-16}$	-0.046	0.675 $2.2 * 10^{-16}$
section 3: km 20.100 - km 20.470	-0.022	0.659 $3.6 * 10^{-7}$	-0.134	0.467 0.0006
section 3: km 21.755 - km 22.800	-0.138	0.285 0.0001	0.039	0.262 0.0004

The results in Table 22 show quite low medians for the absolute deviations of the two track quality parameters. Higher deviations can be observed for segments in the new section 3. This could be explained by the initial settlements after track renewal that are influenced by many factors. Therefore, track geometry is more difficult to predict at this stage compared to a track at a later point in service life. However, the correlation analyses for all sections indicate p-values clearly below 0.05. This means there is a statistically significant correlation between the predicted and the real track quality parameters for all analysed sections in every case. It must be stated that it is not possible to compare the correlation coefficients and the p-values of the examined sections, as they exhibit different lengths and therefore a different number of observations (cross sections).

In total, the executed validation process on short sections shows quite low deviations of the predicted and the real track quality parameters on average. Furthermore, a statistically significant correlation between the predicted and the real values is found in every case. Hence, the prediction model delivers values that match very well with the real situation and track quality parameters after tamping can be predicted accurately.

By comparing predicted and actually executed tamping tasks, one section is particularly noticeable: Between km 18.200 and km 19.000 in test section 3, no tamping action is predicted by *4tamp*^{ing}. In contrast, four tasks were executed between 2010 and 2015 in reality. By looking in detail at this section, it turns out that there is quite a confusing situation that cannot be covered by the prediction model:

- The first task was executed in 2010. This was stabilisation tamping and therefore a part of total renewal and out of scope of the present schedule.
- After stabilisation tamping, a very high deterioration rate (0.5 mm/year) can be observed on average. This is an indication of a defective execution of stabilisation tamping. Hence, it was necessary to execute another task in 2011 in order to improve the poor deterioration rate.
- In the next deterioration period, only one measuring run is available, and no track quality parameters could be calculated. Therefore, it is also not possible to investigate the influences on the deterioration rate. Nevertheless, also in 2012, a tamping task was executed.
- Afterwards, an average deterioration rate of 0.27 mm/year can be reached in this section. This is not a perfect value but a big improvement compared to 0.5 mm/year directly after stabilisation tamping. This is a strong piece of evidence for the finding in chapter 8.3.1 that it is possible to improve poor track quality parameters by means of a high tamping effort (in this case: annual tamping interval at the beginning of service life).
- The next intervention in 2015 is part of a longer task and therefore comprehensible in order to reach preferably continuous actions. That said, the tamping interval is still comparable high for a new track.

This special case shows the wide-ranging consequences of a faulty execution of a stabilisation tamping task. As this thesis focuses on tamping tasks executed in the form of maintenance, stabilisation tamping is outside of its scope, and this very special situation is not covered by the optimised schedule.

10.4 Economical evaluation

The previous sections clearly show the potential and the possible prolongation of service life through the application of an optimised tamping strategy. The goal of the present chapter is to test these findings on their influence on the economic situation.

Therefore, the life cycle costs (LCC) of different strategies are calculated and compared. The LCC are composed of three main components: (i) depreciation, (ii) costs of operational hindrances (COH) and (iii) maintenance costs [113].

As the different strategies lead to varying service lives, the average costs per year are used for the comparison rather than the total life cycle costs. The cost rates for the different positions are taken from the standard elements (chapter 4.1). For the present comparison, the standard element with the following configuration is chosen:

- Traffic load: 45,000 – 70,000 gt/d
- Radius: > 3,000 m
- Sleeper: concrete
- Rail: 60E1 R260
- Subsoil: good condition

10.4.1 Evaluation for base scenarios

In the first step, the basic strategies for tracks with poor (chapter 8.3.1) and good quality (chapter 8.3.2) are analysed regarding their economic impacts. Therefore, the working cycle of the standard element and the life span are adapted to the reachable service life of the considered strategy.

Figure 77 shows the results of the three examined strategies for a track with poor quality. For every strategy, the depreciation is depicted in green, the costs of operational hindrance in blue, the maintenance costs in yellow and the total life cycle costs in red. In the left picture, the result for a compliant ILE is visible. In the subsequent considerations, this case is considered as the base scenario and is therefore determined with 100 %.

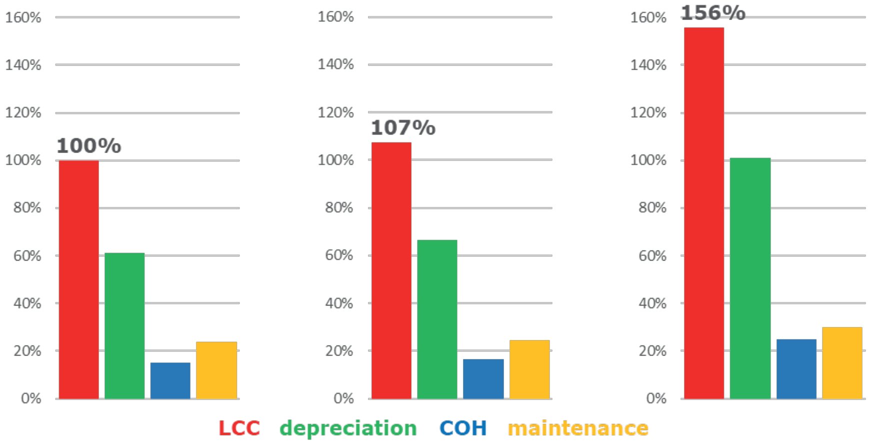


Figure 77: Life cycle costs for tracks with poor quality with a constant ILE (left), a compliant ILE (middle) and an ILE for optimising track quality (right).

The results show that a compliant ILE leads to an increase in LCC by 7 % (Figure 77, middle). It has been found that it is possible to restore poor track quality parameters in the beginning and to optimise them further on. However, the effort is very high and the present economic analyses show that the LCC increase by 56 % if this strategy is pursued (Figure 77, right).

In Figure 78, the results of the investigated strategies for a track with good track quality are displayed. Again, the percentages are related to the base scenario from before (track with poor quality, constant ILE). The left picture shows the results for the constant intervention level. The result indicates only a minor improvement of 4 % compared to the base scenario, although the initial quality parameters are much better. Hence, this compliant ILE must be the wrong strategy for this configuration. The picture in the middle shows the results for a compliant ILE. It is thus already possible to decrease the total LCC by 16 %. If the compliant ILE is further optimised, it is possible to reduce life cycle costs by 20 % compared to the base scenario. This is shown in the right picture of Figure 78. To reach such a reduction in LCC, two prerequisites are necessary: comparably good initial track quality parameters and an optimised tamping strategy.

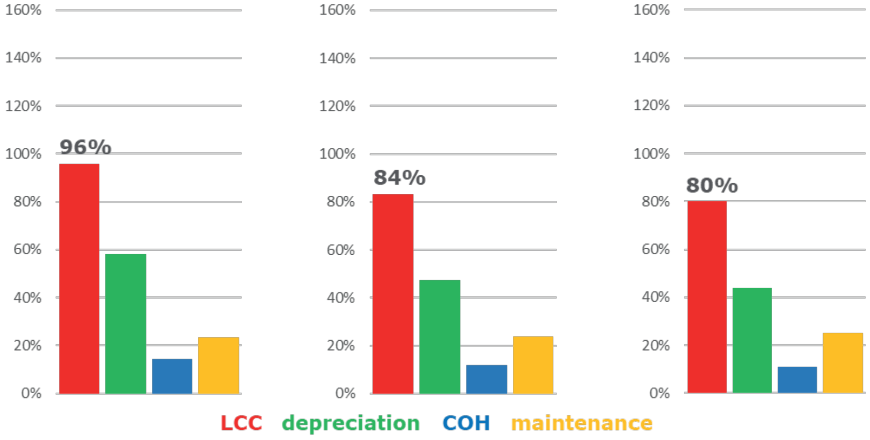


Figure 78: Life cycle costs for tracks with good quality with a constant ILE (left), a compliant ILE (middle) and an optimised compliant ILE (right).

The above described scenarios exhibit differences in LCC mainly due to varying service lives, while the number of tamping tasks is always the same. However, it would be also possible to reduce the amount of tamping actions. This approach is shown in Figure 79. The left picture displays the scenario for a track of good quality and an optimised compliant ILE. The right picture shows the situation with the same quality parameters and intervention levels but with only seven instead of ten tamping tasks. As the results indicate, this reduction leads to an increase in LCC.

The reason for this is the reduced service life which is caused by the decreased maintenance effort. In summary, this example shows that reducing maintenance is a theoretical option. However, prolonging service life due to an optimised tamping strategy together with a constant tamping effort is the most reasonable solution.

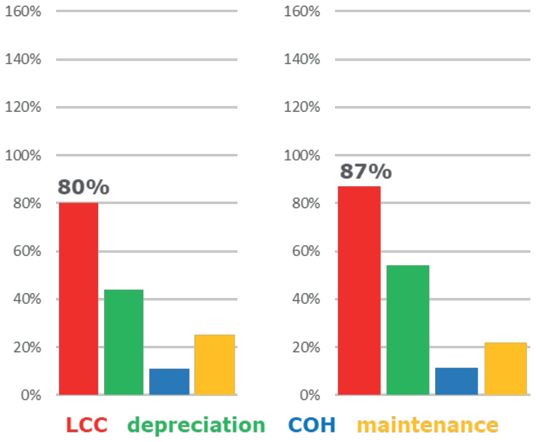


Figure 79: Life cycle costs for tracks with good quality with an optimised compliant ILE and a normal (left) and a reduced maintenance effort (right).

10.4.2 Evaluation for test sections

Besides the economical evaluation of the basic strategies from chapter 8.3.1 and 8.3.2, the results from the test sections are also investigated with regard to their impact on LCC. Therefore, the same methodology is used as before. In this case, the LCC of the actually executed strategy always serve as a base scenario and are therefore set at 100 %. A summary of the results is shown in Table 23. Due to the prolongation in service life, it is possible to decrease the life cycle costs in all three analysed sections by applying the optimised tamping schedule. A reduction of 36 % in section 1, 7 % in section 2 and a 17 % decrease in life cycle costs in section 3 can be achieved in comparison to the actually executed strategy.

Table 23: Comparison of the life cycle costs for executed and predicted tamping strategy.

	LCC executed	LCC predicted	LCC reduction
section 1	100%	64%	36%
section 2	100%	93%	7%
section 3	100%	83%	17%
total	100%	80%	**20%**

For all three analysed sections together, a reduction in life cycle costs of 20 % can be achieved. This result is shown in detail in Figure 80. The left picture contains the LCC of the executed strategy as a base scenario and the right picture shows the situation in which the optimised strategy is applied.

In summary, it can be stated that it is possible to reduce LCC significantly by applying an optimised tamping strategy. This is proven for base scenarios for one cross section and also for longer sections where the outcomes are compared with results in reality.

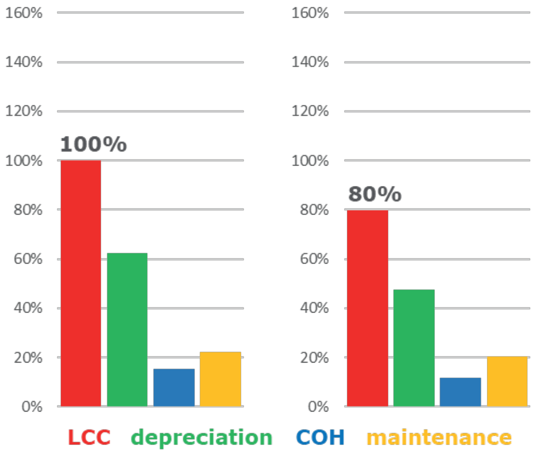


Figure 80: Life cycle costs for the three test sections with executed (left) and predicted (right) tamping strategy.

11

Maintenance planning within life cycle management

The previous chapters deal with optimised tamping scheduling based on track geometry data. In this chapter, the goal is to see the planning of tamping actions in a broader context. Therefore, the interconnections between scheduled tamping tasks and other necessary maintenance/renewal activities must be considered. In this regard, two cases might appear that would make the execution of tamping tasks superfluous in the upcoming years:

- In case of a fouled ballast bed where the ballast layer has reached the end of its service life, tamping does not show durable effects anymore. Track geometry can only be restored to a specific degree, and afterwards the degradation rate is very high. This would lead to an uneconomically high tamping interval. Hence, tamping is no longer the right option, and more complex measures like wet spot repair on short sections or ballast cleaning on longer sections must be executed. Furthermore, these measures are quite costly and therefore often equal the end of the economic service life of the track (chapter 11.3). Thus, a total renewal should be executed instead of the measure. Both scenarios – complex maintenance tasks on the ballast bed and total renewal – lead to a completely changed situation, as the ballast bed is renewed. Hence, it would not make sense to plan tamping tasks based on the current boundary conditions beyond the measures.

- In some cases, other components besides the ballast bed will reach the end of their service life in the upcoming years. Therefore, comprehensive actions for these components will become necessary. In some instances – e.g. if an extensive single sleeper exchange is necessary – this situation also leads to a total renewal instead of the maintenance measure. In this event, scheduling of tamping tasks based on the present situation beyond the renewal would not be reasonable either.

The situations described above show that it is essential to consider two topics in order to see tamping scheduling in combination with the whole track construction:

- It is necessary to monitor the current condition of the different components of the track and its development over time.
- If it is necessary to exchange a component within the track construction, it must be decided whether the replacement is carried out in the form of maintenance or whether a total renewal is the more reasonable option.

The following sub-chapters deal with precisely these issues. At first, methods are explained to evaluate the ballast condition. Afterwards, the condition evaluation of other relevant track components is discussed. As a last step, the approach of life cycle management (LCM) is introduced to determine the optimal point in time for track renewal.

11.1 Ballast condition

The simplest method for evaluating the ballast condition would be the assessment based on a visual inspection. Based on the visual inspection, a complete overview of the conditions on site can be gained. However, this method has some disadvantages: besides the subjectivity of the assessment, the evaluation is very time-consuming and costly. The main drawback is that only the surface of the ballast bed can be assessed; and, when a fouled ballast is already visible at the top of the layer, it is much too late for maintenance optimisation, and immediate actions are necessary. To counter these shortcomings, different methods were developed to evaluate ballast condition in an appropriate way. The most common approaches are shortly introduced in the following chapters.

11.1.1 Geotechnical survey

A geotechnical survey is the most accurate method for assessing the ballast condition. Therefore, the ballast is removed manually or by means of an excavator (Figure 81, left). Regarding the ERRI report D 182 RP2 [142], it is recommended that the ballast be excavated by means of a special steel frame.

This methodology should guarantee the complete removal of the defined sample volume and ensure accurate results. This procedure is also contained in the standard EN 13450 [16]. After the excavation, the ballast material is brought to the laboratory, where the sample is sieved and the grain size distribution is determined with reference to normative regulated procedures [143]. Based on the proportion of fine grains, the degree of ballast fouling can be determined. Therefore, in Austria, grains < 22.4 mm are defined as fine material [15]. If this fraction exceeds a proportion of 30 %, regarding the ERRI report D 182 RP1 [129], the indication for an inadequate ballast condition is given, and ballast cleaning might be necessary [130]. Besides the grain size distribution, it is possible to execute other, detailed analyses like LA, micro-deval and impact tests or further innovative examinations at the laboratory [144].

Geotechnical surveys show the advantages of high accuracy and the possibility for detailed evaluations. Furthermore, it is possible to assess the bearing capacity of subjacent layers (e.g. bearing layer), as shown in the right picture of Figure 81.

Figure 81: Geotechnical survey.

However, geotechnical surveys are quite complex measures that are very time-consuming and costly. To execute the procedure, a temporary track closure is necessary, thus limiting track availability. After the excavation, a tamping action must be performed in most cases to restore the homogeneity of the ballast layer. Even if such a survey delivers very detailed results, the evaluation can only be performed for single spots. Due to the mentioned properties, geotechnical surveys are suitable to gain detailed information in locally restricted areas which are of particular interest. That said, it would not be reasonable to investigate the ballast condition network-wide over time.

11.1.2 Ground-penetrating radar

Another possibility for evaluating the ballast condition provides the ground-penetrating radar (GPR). This geophysical measuring system is both a transmitter and a receiver of electromagnetic impulses. The properties of different materials can be derived from the transit time and intensity of the impulses. Depending on the dielectric constant, the electromagnetic impulses introduced reflect at different speeds and intensities from the various materials. The different reflections can then be calculated and displayed as a function of time and amplitude. A specific colour code is assigned to this function, and by stringing together the individual measurements, a radargram is created [145].

Although the radargram allows for a graphical analysis of the data, it is unsuitable for a common representation and illustration of the results. Hence, different indicators were developed to record and display the results in a clear way [146] [147] [148]. Figure 82 shows different indicators summarising the results from a GPR measuring run and allow for a simple interpretation of the results. This visualisation comes from Ground Control Geophysics & Consulting GmbH and is currently used by the Austrian Federal Railways. In a longitudinal section of the track, the thickness of the ballast bed is shown for polluted and unpolluted sections, as well as the intermediate layer underneath.

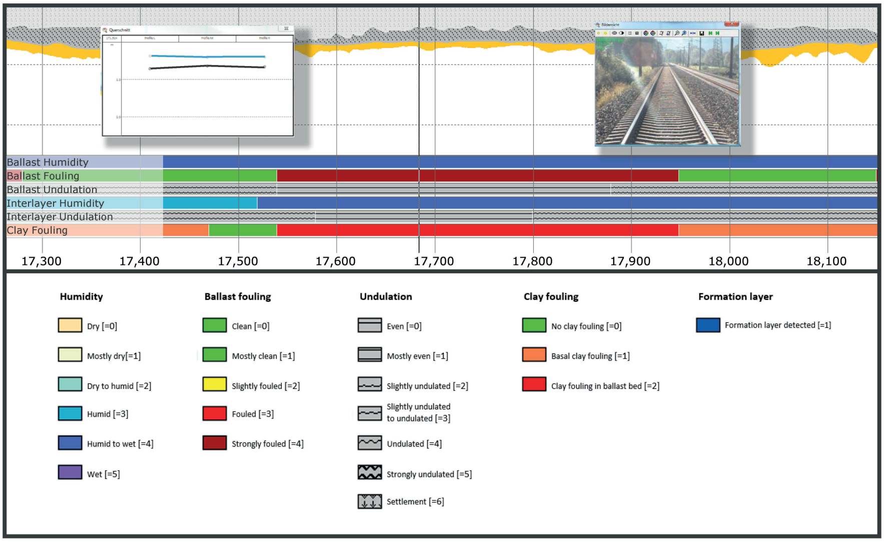


Figure 82: Indicators for interpreting the results of a GPR run [59].

The advantage of this method is its reproducibility and objectivity. Theoretically, the GPR measuring device can be mounted on measuring cars. In this case, the measurement can be executed within a standard measuring run at high speeds. However, most standard measuring cars are not additionally equipped with GPR devices. In this case, a separate measuring run with the GPR and therefore an additional train slot is required. Nonetheless, in both cases, longer sections can be investigated within a comparably short time. Another disadvantage of the system is the data processing and evaluation procedure, which is extremely complex and time-consuming.

11.1.3 Fractal analysis

Although the methodologies introduced above show some advantages, there are still drawbacks with regard to conducting a network-wide evaluation of the ballast condition in a reproducible way and within a reasonable period of time. However, there is an approach, meeting these requirements: the fractal analysis of vertical track geometry.

The concept of fractal analysis is not new. Mandelbrot [149] developed it in 1967 as an answer to an essentially fictional problem – not thinking of its possible benefits for the rail industry. His considerations focused on a historical question: the exact length of the coastline of Great Britain. As it was impossible to approximate the length of the karstic coastline of Great Britain with sufficient accuracy using Euclidean geometry, Mandelbrot tried to do so using a polygonal chain. This is how he developed the Modified Divider Method [150], which is a specific form of fractal analysis.

In 2002, Hyslip [151] realised the potential of this method for analysing railway track geometry and tested the calculation method on a corridor section of AMTRAK. This approach was refined and implemented for some 4,400 km of track in Austria for measuring runs of over 15 years. Thus, it became possible to conduct analyses of this kind on a major scale for the first time [152].

This analysis methodology is based on the fact that vertical track geometry can be derived from a sum of harmonic irregularities with different wavelengths and their amplitudes. Mean values or standard deviations, as they are commonly used, focus on the amplitude of defects within the alignment, but neglect the wavelength, i.e. the characteristic of a failure. Fractal analyses of vertical track geometry describe the characteristics of a failure by analysing the wavelengths of the signal. Therefore, the modified divider length method is used.

Within this method, a data segment (in the specific case 150 m) is iteratively subdivided into progressively smaller sections λ, and the associated measuring point Y_i is determined. Afterwards, the lengths of the polygons stretched between the points are calculated and summed (Figure 83, left).

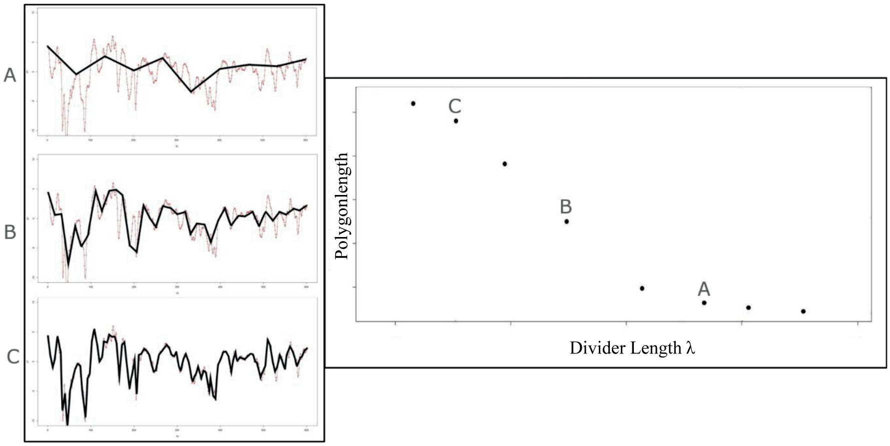


Figure 83: Iteration of divider length (left) and creation of Richardson plot (right) [59] [66].

The progressively increasing polygon lengths (ordinates) and progressively decreasing segment lengths (abscissae) are subsequently displayed in a logarithmic diagram. This diagram is called a Richardson plot. The procedure is shown in the right picture of Figure 83. In the next step, the different fractal dimensions are described by a regression line. In this context, the three dimensions represent short- (1 m – 3 m), medium- (3 m – 25 m) and long-wave (25 m – 70 m) track irregularities. The slope of the calculated regression line shows the expression of the respective wave range in the data segment.

Higher values cause a stronger representation of the observed wave range in the data segment, while lower values describe a weaker expression. Examples of two different cases are shown in Figure 84.

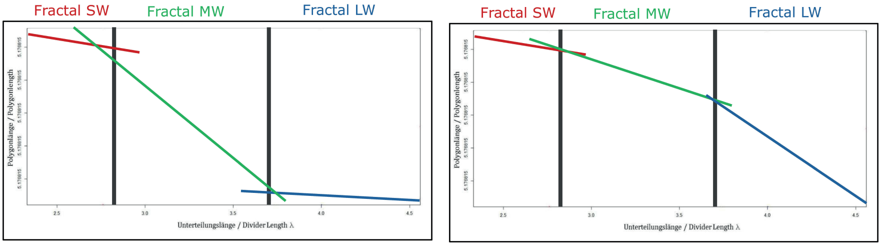


Figure 84: Richardson plot with increased gradient in the medium (left) and long wavelength range (right) [66] [59].

Deflections in vertical track geometry caused by ballast problems are more likely to occur within the mid-waved range (Figure 84, left), while deflections caused by insufficient substructure conditions are expected to appear as wavelengths larger than 25 m (Figure 84, right). The short wavelength range has not yet been studied in the same depth. However, first attempts have shown that short-waved errors may implicate an inadequate interaction between sleepers and ballast within the upper ballast layer also known as “hanging sleeper” [153]. The whole methodology is summarised in Figure 85.

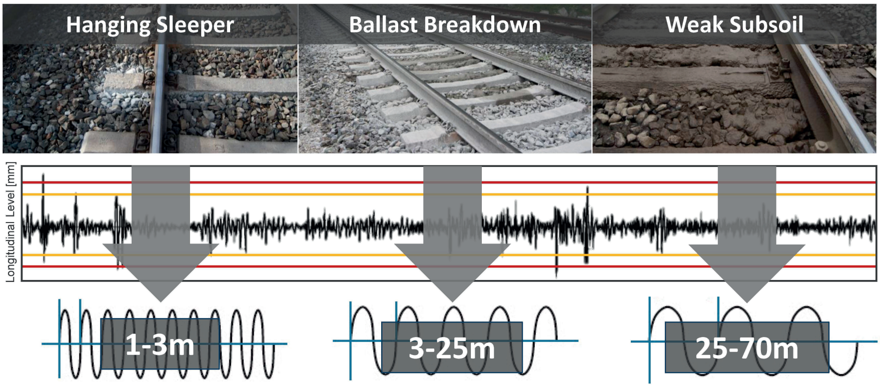


Figure 85: Methodology of fractal analyses of vertical track geometry [154].

The methodology of fractal analysis and its fields of application were evaluated within an extensive validation process [59]. As part of this process, network-wide analyses were carried out as well as comparisons with section-specific results from other evaluation methods like GPR or geotechnical surveys. All the executed validations could confirm the huge potential of fractal analysis in condition evaluation for the railway track.

This means, by considering the mid-waved range, a ballast evaluation is possible without any additional effort because all required information can be extracted from the signal of longitudinal level that is generated by the measuring car. This condition evaluation can be carried out with comparably low computing effort. Furthermore, it is possible to execute sophisticated time series analyses, as the values can be re-calculated up to the point where data of longitudinal level are available.

11.2 Condition of further track components

Besides the ballast bed, the rail and the sleepers together with the fastening system are the main components of the railway superstructure. This applies for the tasks that have to be fulfilled as well as for the related maintenance and replacement costs. Hence, the condition monitoring of these components is briefly discussed in the following.

11.2.1 Rail condition

Rails represent the direct contact area between vehicles (wheels) and infrastructure. It is their task to distribute the high punctiform loads that occur to the underlying components. Hence, rails are exposed to several wear mechanisms, and different methods exist to monitor rail condition non-destructively [4] [155]:

- Ultrasonic testing trains (Figure 86) are used for detecting failures in transverse and longitudinal direction within the rail material. Therefore, the ultrasonic transmitter is coupled with the rail by means of oil or water. Rail defects generate a failure echo, which can be recorded. The measuring runs are carried out at speeds between 40 km/h up to a maximum of 110 km/h at specific intervals. Additionally, hand-held testing devices are used for checking the results. This is especially important in turnouts to capture all components, particularly the crossing nose.
- Eddy current measurements allow the detection of tiny open cracks on the rail surface (“head-checks”), referred to as rolling contact fatigue (RCF). Within the measurement, an alternating magnetic field is created on the rail by means of four-channel eddy-current-probes. The probes roll on the rail for a distance of 0.5 mm. Through magnetic induction, eddy currents arise and can be measured and recorded. As the rail has ferromagnetic properties, eddy currents do not penetrate into the material and move on the rail surface. In areas where cracks appear, eddy currents flow along the crack’s flanks. By means of a penetration angle of 25 °, the crack depth can be calculated.

- Special laser and camera systems make it possible to determine the rail profile. The measured profile is compared with target profiles, and the deviations are calculated. By means of these systems, rail wear (side and height wear) can be measured and monitored. This is especially important for rails in narrow curves.
- Another measuring system are rail surface scans. These are equipped with lasers that measure the absolute altitude every 5 mm by means of a three-point measuring court. These systems enable the detection of rail surface failures such as corrugation in short as well as medium wavelength ranges. The measurements can be carried out with speeds up to 160 km/h.

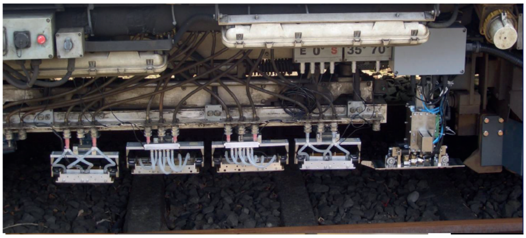


Figure 86: Ultrasonic measuring device on a measuring train [155].

Rail failures can be dealt with to a certain point by rail grinding or milling (depending on crack depth, material abrasion, deformation). If specific limits are exceeded or the wear reserve within the rails is exhausted, a rail exchange is necessary. In contrast to other major spot-related measures (e.g. single sleeper exchange, ballast cleaning), rail exchange as a sole measure can be economic as rails can be replaced without influencing other track components negatively.

11.2.2 Condition of sleepers, fasteners and rail pads

Sleepers and their adjacent components are essential parts of any track construction as they distribute loads from the rail to the underlying ballast bed and are intended to keep track gauge within a specific range. For evaluating the condition of these components, the “noise” of the track gauge signal has to be analysed. In principle, this is possible by calculating the standard deviation of the gauge signal. However, track gauge exhibits some particularities: (i) the measurement signal is not scattered around a fixed value (e.g. zero line); and instead it can take on values ranging from minus 10 mm to plus 35 mm, and even beyond, (ii) track gauge tends to yield higher values in curves. In some cases, gauge widening is installed deliberately in curved areas for improved train running performance.

Hence, a calculated standard deviation of the track gauge signal would be significantly affected by these long-waved signal characteristics. This is particularly evident in transition zones, which cause a rapid change within the calculated values.

At the same time, the short and medium wavelength noise is strongly under-represented. This problem is treated by application of a high-pass filter, which lets signal components with frequencies above its cut-off frequency pass, while erasing signal characteristics with lower frequencies. For this filtering approach, the delta between the raw signal and its moving average is calculated with a constraint length of 25 m. This results in a modified gauge signal, which scatters around the zero line and no longer responds to long-wave influences. Based on this modified signal, the standard deviation is calculated (methodology of standard deviation of modified track gauge), quantifying the force interaction between fastenings and sleepers [59] [66].

In the case of poor force transmission between wooden sleepers and screws, it is possible to execute screw-hole renewal as a maintenance action. Figure 87 shows the measurement signal of track gauge as well as the modified signal and its standard deviation for a track section of 100 m. The latest value of standard deviation of modified track gauge differs fundamentally when compared to the earlier condition. This massive improvement can rarely be seen within the initial measurement values of track gauge. After analysing the related track section in situ, it could be verified that track maintenance was carried out in the form of a screw-hole renewal. Thus, the force transmission between the wooden sleeper and the screws was improved in this area, which counteracts the jittering within the signal. As a result, the value of standard deviation of modified track gauge decreases. This shows that standard deviation of modified track gauge, in contrast to the untreated signal of track gauge itself, provides a condition evaluation of sleepers together with an evaluation of force transmission between sleepers and fastenings.

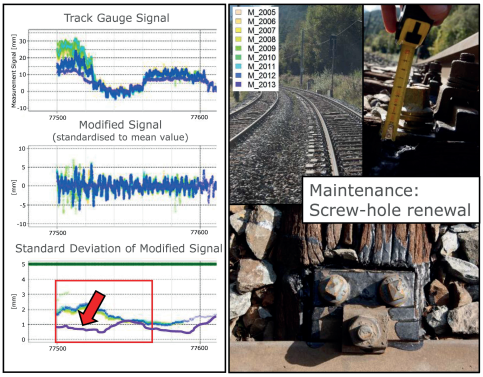


Figure 87: Methodology standard deviation of modified track gauge [154].

If – based on the prognosis – screw-hole renewal is no longer expected to show positive effects, or if sleepers are broken, a sleeper replacement has to be executed. In case of concrete sleepers, a decreasing value of standard deviation of modified track gauge determines the necessity of a rail pad exchange.

11.3 Life cycle management

After evaluating the condition, all maintenance tasks for different components can be derived for the next few years. However, at the end of the service life in particular, it may no longer be reasonable to execute the necessary tasks in the form of maintenance as the economic service life of the track may already have been reached. Thus, one question remains in terms of sustainable railway infrastructure asset management: Is ongoing maintenance the sustainable approach for this track section or would a total renewal be the more economical solution in the LCC context. The answer lies in combining both technical and economic considerations within the methodology of life cycle management (LCM) [156].

The execution of an adequate life cycle management (LCM) approach enables long-term balancing of the maintenance and renewal demands on an efficient and minimum cost level. The aim is to keep the required track quality for as long as possible by means of effective maintenance measures, but also to execute track renewal as soon as it is required. This can be achieved by considering life cycle costs which are explained in chapter 10.4.

From an economic point of view, depreciation decreases with increasing service life. As long as depreciation is the main influence factor, the decrease follows an exponential function due to the 1/n relation.

The costs of maintenance and consequently the costs of operational hindrances, however, are becoming a growing factor over time. As a result, annuities [157] reach their minimum when the incremental decrease of depreciation is lower than the incremental increase in the costs associated with maintenance and operational hindrances. The ideal point in time for track renewal is therefore defined by the minimum of annuities and equals the economic service life of track [30]. This relation can be expressed by the formula:

$$\frac{dD}{dt} = \frac{\frac{dM}{a} + \frac{dCOH}{a}}{dt} \tag{32}$$

D depreciation
M/a maintenance per year
COH/a costs of operational hindrance per year
dt increment of time

This definition is valid under the assumption that renewed track has the same life cycle costs (LCC) as the old track. If new track results in an LCC reduction, these savings reduce the economic service life of existing track. This can be implemented into the calculation by adding savings resulting from earlier re-investments.

In other words, the ideal time for re-investment is when maintenance no longer makes sense due to the advanced wear of a single or several components. Technically, this point can be defined using the introduced approach of component-specific condition evaluation. Based on this method, it is possible to describe and predict quality behaviour of different components over time. Together with prediction models, this approach allows a prognosis to be made of the necessary maintenance tasks. This crucial input has to be combined with cost data for the different measures. Subsequently, it is possible to calculate the annuity curve (sum of depreciation, maintenance costs and costs of operational hindrances divided by service life) for specific track sections. The required input data is asset information such as age and type of superstructure and the necessary maintenance actions for the upcoming year. For this purpose, it is not the amount, but rather the underlying costs of the maintenance measures that are required. This allows the ideal point in time for reinvestment to be determined not only from a technical, but also from an economic perspective [154].

Figure 88 shows an annuity curve for a specific track section as an example together with the executed and predicted maintenance tasks. Because of the high depreciation and low maintenance costs at the beginning of the service life, the curve decreases exponentially in the first years.

This implies that executing larger interventions in the form of maintenance can be often economically reasonable at the beginning or in the middle of the service life [50]. In contrast to this, the same actions might no longer be reasonable in the form of maintenance at the end of the life cycle, and a total renewal is the preferable option.

It must be stated that a tamping action incurs relatively low costs when compared to other maintenance tasks like ballast cleaning or comprehensive single sleeper or rail exchanges. Hence, a global minimum in the annuity curve will not be reached due to a single tamping measure. Nevertheless, other necessary maintenance actions may significantly affect the planning of tamping tasks in the upcoming years.

This can be explained by the example in Figure 88. In 2012, rail exchange was necessary, causing a sudden increase in the annuity function. As annuities are decreasing again afterwards and reaching values below the local minimum in 2011, it was reasonable to carry out the rail exchange in 2012 in the form of single maintenance activity. Furthermore, the measure did not have any consequences for planning tamping actions, as the task has no influence on the ballast bed. Based on the technical predictions, ballast cleaning would be necessary in 2021.

Since ballast cleaning, as a stand-alone measure, is a very costly task, it would cause a sharp and sudden increase in the annuity curve for this year. In contrast to the rail exchange of 2012, the curve does not reach values below the minimum in 2020 after ballast cleaning.

This means a global minimum is reached in 2020, and a total renewal should be executed instead of executing ballast cleaning in 2021. The total renewal would affect the planning of tamping tasks considerably. As the total renewal includes a renewal of the ballast bed in any case (and in some cases also a subsoil rehabilitation), the condition of the ballast layer improves significantly. This means planning tamping actions based on the previous situation beyond the year 2021 would not make sense and leads to wrong conclusions.

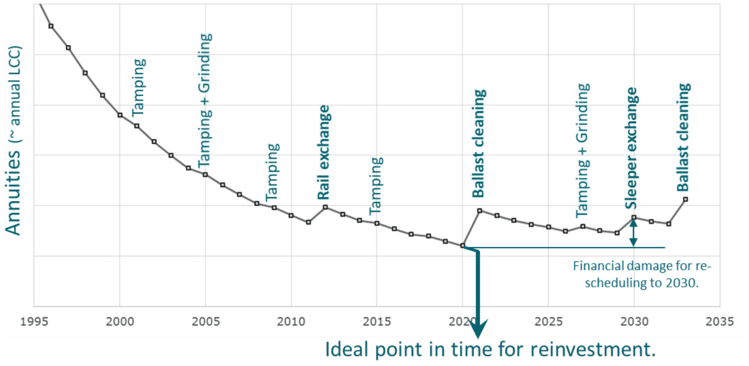


Figure 88: Annuity curve for a track section and calculation of the ideal point in time for re-investment [154].

Apart from answering the question of whether ongoing maintenance or total renewal is the most economic approach, the present methodology offers an additional major advantage: The financial damage for rescheduling the renewal can be calculated [158]. This is done by computing the difference in annuities of the optimal point in time (in Figure 88: 2021) and the rescheduled point in time (in Figure 88: 2030) multiplied by the service life. In this case, ballast cleaning is executed in the form of maintenance in 2021. What's more, this measure leads to a significant change in ballast condition and therefore the adaption of tamping scheduling to the new boundary conditions is required. Table 24 gives an overview of different measures and the necessity of adapting tamping scheduling because of their impacts on the ballast bed.

Table 24: Necessity of adapting tamping scheduling due to different measures.

	in form of maintenance	within total renewal
rail exchange	X	✓
sleeper exchange	(X)*	✓
ballast cleaning	✓	✓

* Tamping is necessary directly after the measure; However, the ballast bed remains and no mid- to long-term effects on tamping scheduling have to be expected.

12

Additional boundary conditions

The tamping schedule developed in this thesis is mainly based on the intervention at an optimal limit to enhance the reachable service life and therefore to optimise life cycle costs. To make the maintenance plan applicable in practice, it is necessary to consider technical constraint points like bridges or turnouts, minimum working lengths and minimum gaps between different tasks (chapter 9.1). In chapter 9.2, the algorithm *4tamp*^{ing} is developed that combines all these parameters to an optimal and executable tamping schedule. However, within a real maintenance planning process, there is a range of further parameters influencing the decisions.

On the one hand, by addressing these factors, there will be deviation from the optimal schedule. On the other hand, the importance of the different parameters depends on many things, such as the goals of the infrastructure manager, the available resources or the general boundary conditions in a track section. Hence, it is quite difficult to consider all the further parameters within an automated maintenance plan. Nevertheless, the additional parameters for making maintenance decisions regarding tamping are introduced below. In general, it should be the goal to establish an expert system where the automated and optimised schedule is used and, where appropriated, modified by the user due to the specific and current boundary conditions. How this can work is explained by means of the examples of a test section. Subsequently, the most important further boundary conditions are briefly discussed together with their influence on scheduling tamping tasks.

12.1 Temporary track closure

As it is not possible to execute tamping tasks and to run trains on the same track at the same time, it is necessary to close a track temporarily while tamping. Such a temporary track closure has negative effects on availability and delays, re-routings, replacement services or the cancellation of connections are resulting. These effects can be expressed by means of the costs of operational hindrances, which quantify the consequences of the non-availability of a track [159]. These costs highly depend on the traffic volume of the considered line, the number of parallel tracks and the possibilities for rerouting trains. As temporary track closures are in contrast to train operations, closures are rarely an available option and therefore have to be planned and used in the most reasonable way. This is especially true for lines with a high traffic volume and low remaining capacities.

One question that always arises is: Is it more reasonable to close longer sections for a longer time or to execute the works in short closures and sections? Unfortunately, this question cannot be answered in general terms.

The first option allows for the continuous execution of the works, leading to more continuous quality. Furthermore, the unit costs are comparably low and the shift performance is high as long sections are maintained without interruptions. In this case, high performance machinery can show its advantages, and both travel and set-up times can be reduced significantly. Executing only short sections brings the advantage of more flexibility and availability. This might be an option for lines with high requirements on capacity. For example, it is possible to plan the closures in such a way that important train traffic (e.g. long-distance trains) can be sustained. Another question that arises is whether the tasks should be executed during the day, during the night or during weekends. Working during the night or weekends, normally brings the advantage of higher availability, as the traffic volume is lower. To execute the works during the day mostly results in a severe limitation of availability but decreases the labour costs, as no bonuses for night or weekend work must be paid. To answer these questions in a sustainable way, a comparison of occurring costs of operational hindrances and working costs has to be done. Within this comparison, the circumstances of the considered section must be introduced. Hence, the resulting strategy can be different for a high loaded main line in comparison to a branch line for example – this is especially true for the maintenance task of tamping [160].

12.2 Unit costs

Unit costs describe the costs for a maintenance task per unit. One example for this would be the tamping costs for one meter. In principle, the output per shift is increasing and therefore the unit costs are decreasing with higher section lengths. This is due to the omission of multiple set-up and travel processes and the high productivity of big machinery can be exploited.

In practice, most maintenance tasks are executed by external construction companies and not by the infrastructure manager itself. This means the influence of the infrastructure manager on unit costs highly depends on the contracts between the two parties. For example, it is not possible to optimise unit costs when the contract contains a fixed price for one meter of tamping. In this case, the infrastructure manager has no interest in making the best use of resources within the planning of section lengths. On the other hand, the construction company is free to choose a machine and thus determine the duration of the works. A machine with lower performance would lead to a longer construction period, but the price would be always the same. The situation would be different if the price per shift was fixed instead of the unit costs. In this case, the infrastructure manager has major incentive to optimise the output in meters as the unit costs decrease with an increasing output per shift, as the price for the shift always remains the same. In practice, contract models are often used where the two approaches are combined.

This can be realised for example by agreeing a fixed price per shift that includes a specific working length. If the actually executed lengths are significantly higher or lower, supplements or discounts are charged.

12.3 Budget

Every region within a railway network receives a monetary amount for a specific period of time for the execution of maintenance tasks. Besides increasing traffic volumes, infrastructure managers are often faced with the challenge of budget restrictions. It is quite easy to gain short-term savings by reducing amounts for maintenance and renewal. However, this strategy will lead to a cost increase on a large scale from a long-term perspective, as the consequences will become apparent a few years later [30]. In some cases, budgets are also shifted from one task to another at short notice, as it is more urgent to execute the other task. Therefore, it is essential to provide enough budgets for the required tasks and to spend them in the most reasonable way to guarantee a sustainable situation for the upcoming years and decades.

In some special cases, more financial resources are available as required. In these cases, the budgets are often spent anyway as otherwise budget restrictions are feared in the next period.

12.4 Tamping machines

The tamping machines used have significant influence on the planning process of tamping tasks. Over the years, the performance of tamping machines has increased rapidly. Early automated machines were able to treat 120 m/h. Today, four-sleeper tamping machines are available with a performance of up to 2,600 m/h [161]. Normally, executing construction companies have machinery with different properties and performances at their disposal. When deploying them, it must be considered that different properties are more or less suitable for specific applications [162]. For example, flexible one-sleeper tamping machines are appropriate for short sections, single failures and turnouts. By contrast, high-performance machinery with the possibility of tamping the ballast underneath several sleepers at the same time are suitable for long continuous sections without any interruption to the work. However, conversely, the availability of the machines has significant influence on the executable tamping schedule. For example, it is difficult to tamp several long sections when only a one-sleeper tamping machine is available for a comparatively short time.

12.5 Staff

Another important factor for the scheduling of tamping actions is the working staff executing the tasks. Tamping machines are quite complex construction machines needing specially educated teams to operate them. This means there must be enough skilled personnel on hand to execute the desired schedules. In most cases, one team is responsible for one machine as well as the execution of the works on the construction site. Therefore, the legal regulations regarding working hours and resting periods are also important factors within the planning process.

12.6 Worst acceptable track quality

It must be mentioned that the optimal intervention levels used for the optimal tamping schedule are far off from safety critical limits. Furthermore, the levels used also guarantee sufficient riding comfort. Nevertheless, in some cases, a track quality might be desired that is better than the optimal tamping schedule would suggest.

In this case, tamping tasks must be executed earlier. This improvement of track quality means a deviation from the optimised schedule and therefore increases life cycle costs.

12.7 Uniform track quality

Line tamping is normally executed by correcting track geometry to an absolute level. This means that the track has quite a different position after the measure compared to the enclosing sections. Hence, at the points where the tamping measure starts and ends, an interfering point emerges. Although the transition from the tamped to the surrounding track is smoothed by a ramp [34], these spots are potential places for the occurrence of single failures [29]. In order to counteract this, it is reasonable to execute tamping measures on longer, continuous sections.

12.8 Transition curves

Elements that might influence the tamping schedule are transition curves [80]. In transition curves, both the curvature and the cant are continuously increasing or decreasing respectively. Because of the complex geometry, a tamping task should not begin or end within a transition curve [31]. Data from the recording car are not automatically linked with the detailed alignment, as especially in transition curves, a lot of various solutions can be found in reality. However, if only part of a transition curve is concerned by the schedule, it must be decided whether the whole transition curve is tamped or if it is omitted completely.

12.9 Summary

As the sub-chapters indicate, there are many factors influencing the tamping scheduling process. It must not be forgotten, that all the parameters have interconnections and influence each other. These dependencies and their consequences are explained by means of an example on a test section in chapter 12.10.

However, it can be stated that the adaption of the tamping schedule developed by the algorithm *4tamp*^{ing} due to the factors described above means a deviation from the optimum. This means any adjustment leads to a reduced service life and therefore to increased life cycle costs of the track section.

For example, it may be decided that more or longer sections are to be executed than the automated schedule suggests to reduce unit costs. In this case, cost effects of the length of working sections [163] and non-availability must be related to the additional costs due to the reduction in service life.

In some cases, it is necessary to reduce maintenance amounts compared to the optimal schedule due to insufficient resources (e.g. money, staff, machinery). Therefore, it must be decided which tasks should be executed and which tasks should be postponed. Ideally, this decision is based on reproducible technical and economic evaluations, where the economic damage [158] is calculated for postponing a measure. Due to this damage, it is possible to rank the measures and to adapt the schedule in sections where the potential damage is comparatively low and is overcompensated by additional aspects.

12.10 Example

Possible adaptions due to additional boundary conditions are described my means of an example on test section 2 (chapter 10.1, Figure 72). The process of adjusting the schedule is shown in Figure 89. This section exhibits a comparatively high number of scheduled tamping tasks. Especially at the beginning of the planning horizon, tamping effort is extensive. This indicates that a correction of the tamping strategy is necessary to reach the optimal life cycle costs. This correction can be carried out by means of the extensive tamping tasks in the first three years of the schedule.

Within the present optimised schedule, the years 2012 and 2013 contain potential for adjustments. In 2012, nearly the whole section is intended for a tamping measure. A bigger gap only occurs between km 172.950 and km 173.500. However, within this area, a tamping task is scheduled one year later in 2013. It would therefore be obvious to bring this segment forward one year to 2012. Thus, a long and continuous working length would emerge.

Besides the mentioned bigger gap, in 2012 two smaller gaps between km 174.060 and km 174.280 and between km 174.730 and km 174.910 are omitted in the schedule. Although these areas exceed the value of the defined minimum gap of 100 m, it might be reasonable to include them in the plan for 2012. In the end, these adjustments lead to one continuous task over the whole sections in 2012. This would decrease the number of potential interfering points, lead to more homogenous track quality and might increase the productivity in the shift, as the work can be carried out continuously without interruptions. However, it must be stated that some prerequisites are necessary to implement these adaptions.

On the one hand, the required budget for tamping the whole section, the staff and an appropriate tamping machine must be available. Furthermore, it must be possible to receive the required temporary track closures to execute the works on the whole section. The length of the track closure is in turn dependent on the machine used, as its performance significantly influences the duration of the works. The proposed adaptions bring the advantage that no more tamping measures are scheduled in 2013. This means it is not necessary to provide all resources for only one comparatively short section in this year.

If it is not possible to shift the task from 2013 to 2012 due to the discussed boundary conditions, it might also be an option to postpone the segment to 2014. A reason for this might be an excessively short track closure. In this case, the continuous section in 2014 would be extended, and the benefits of having no task in 2013 can be exploited as well.

Another potential time span for adjusting in the schedule is 2016 and the surrounding years. In 2016, three longer sections are intended for tamping. These sections are separated by comparatively short gaps. As a first step, it would be possible to close these gaps to avoid interfering points and to reach a more continuous track quality. In a subsequent step, it would be possible to shift the single tasks from 2015 and 2017 to the year 2016. This would lead to an extension at the end of the initially planned task and to a remaining gap between km 172.170 and km 172.630. To close this gap, it would even be possible to bring forward the measure from 2018 to 2016. In this case, the result would once again be a continuous tamping task in 2016 within the whole section. To implement these changes, it is again necessary to check the availability of the required resources and temporary track closures. However, in this case, there would be the big advantage that the whole deployment of resources could be bundled into one year, and in 2015, 2017 and 2018 no further tasks would have to be executed in the considered section. The final schedule with the relevant adjustments is depicted in Figure 90.

As already mentioned, the adjustments described above mean deviations from the optimum LCC of the single sections. This means the adaptions must be argued by other factors to generate an overall optimum due to the present boundary conditions. This must be done by track experts within the maintenance planning process based on the optimal schedule.

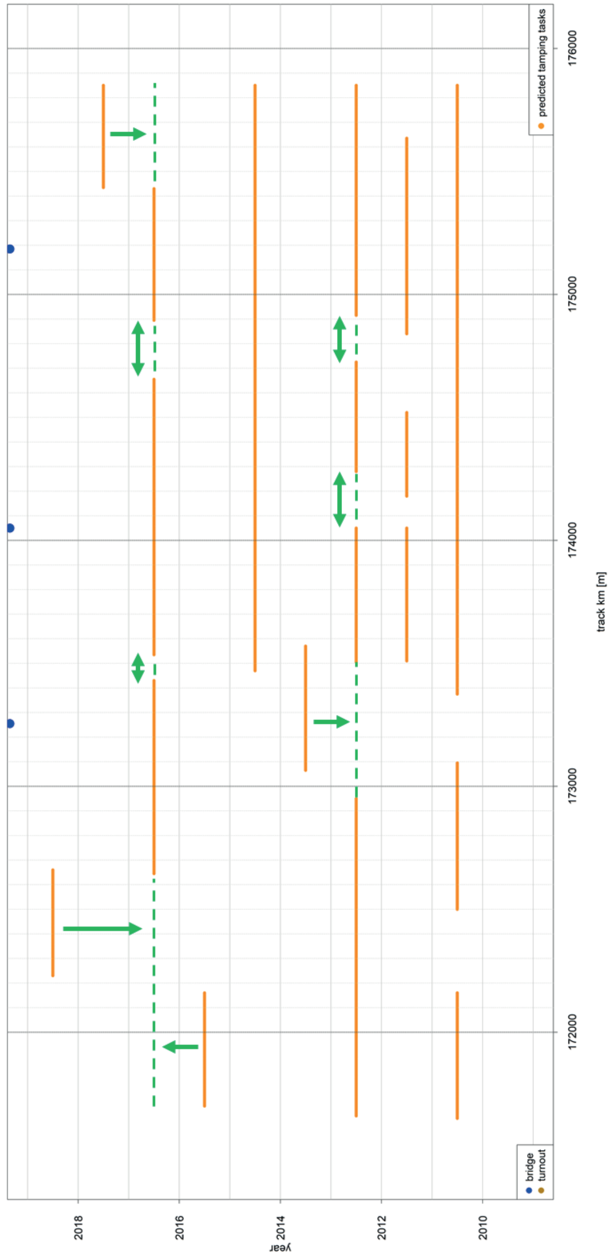


Figure 89: Example of possible adjustments in section 2.

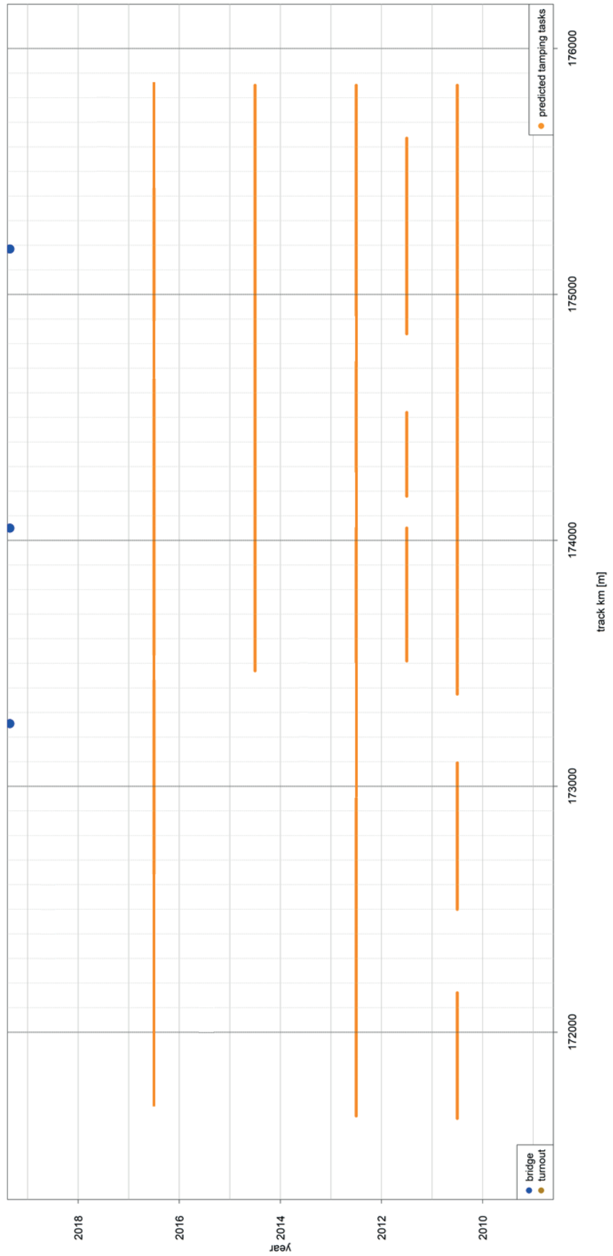


Figure 90: Possible final result 4tamp^{ing} in section 2.

13

Summary and outlook

Tamping restores track geometry and is therefore the most important maintenance task for ballasted track. As the different evaluations in this work show, the point in time at which a tamping task is executed might have significant influence on the reachable service life. Hence, within the present thesis, an automated tamping schedule is developed that is especially based on an optimal intervention level and therefore designed to optimise life cycle costs.

To implement this, it is necessary to investigate the different possibilities to describe track quality as a first step. Within this examination, it turns out that the (modified) standard deviation of longitudinal level is a very good track quality index for making maintenance decisions regarding tamping within a sustainable maintenance regime. Further analyses show that a linear deterioration model is very well suited to describe track quality behaviour over time between two tamping tasks and predict the next action based on measuring data.

For developing a tamping schedule for the upcoming years, it is also necessary to predict more than just the next task. In order to do so, the influence of factors like track quality parameters before the measure, type of superstructure and track age on the quality parameters after tamping are investigated. These findings are summarised in so-called prediction tables that make it possible to determine the track quality behaviour after a tamping measure on the basis of the present boundary conditions. Based on this model, it is also possible to determine overall tamping strategies for a specific type of track.

The analyses show that, for tracks with poor quality, a constant intervention level is the best option, and the tasks should be executed as late as possible (reactive maintenance regime). In contrast, for tracks with good quality, a compliant intervention level should be applied. For these tracks, the potential for optimising the intervention level is very high (preventive maintenance regime). Furthermore, it turns out that the criterion for optimising tamping strategies is not track quality itself, but much more the reachable service life. Analyses show that it is possible to reduce life cycle costs significantly by optimising the tamping strategy. Besides the determination of general strategies, it is possible to calculate the optimal intervention level to any desired situation. Therefore, an algorithm is created to automate this. The deterioration of track quality and also its rectification by tamping are very complex processes influenced by lots of boundary conditions. Particularly for the degradation process, the most important factors are considered within the present theses. However, the tamping process itself, in particular, might contain many more factors that are especially influential on the behaviour after the measure.

Examples of these parameters include the lifting values, the number of penetrations, the compaction values, the frequency, the tamping unit used, among others. Investigating their influence on the track quality behaviour should be part of further research works. In this context, the reverse question also arises, i.e. whether it is possible to gain information regarding the track and especially the ballast condition during the tamping process. In this regard, initial studies by Offenbacher [7] and Barbir et al. [164] are already showing promising results.

The results up to now mainly focus on every cross section separately. However, a railway track is a linear asset, where maintenance tasks – and especially line tamping – are executed over longer sections. Therefore, the sophisticated algorithm *4tamp^{ing}* is created that combines the results of the single cross sections to form reasonable section lengths for tamping for the upcoming years. The basis for this is the ideal point in time for the next tamping intervention. Furthermore, technical constraint points, minimum section lengths and minimum gaps between the sections are considered. These values are not fixed but can be determined individually by the user. In the end, *4tamp^{ing}* delivers an executable tamping schedule for the next years. Within the schedule, the focus is set on line tamping tasks. For future works, it would be interesting to include the correction of single failures as well. Therefore, it is necessary to define the length of a single failure and to investigate its behaviour over time and after spot tamping. Furthermore, criteria must be found for distinguishing between a series of single failures that should be rectified by spot tamping and sections of poor track quality that are corrected by line tamping.

The currently developed algorithm *4tamp*^{ing} is performed for three test sections afterwards. As these tests are processed for past years, it is possible to compare the results with actually executed tasks in this period. In terms of the amounts for tamping, no clear result can be observed. In some cases, *4tamp*^{ing} predicts more and, in some cases, fewer tasks than executed in reality. In contrast, with regard to the reachable service life, the result is clear: by executing the computed schedule of the algorithm *4tamp*^{ing}, it is possible to stretch the service life in any case compared to the actually executed plan. As a result, it is possible to reduce life cycle costs by 20 % on average for all test sections.

Of course, besides the parameters considered in the automated algorithm *4tamp*^{ing}, there are many other factors influencing decisions in tamping scheduling. Available resources like budgets, staff or machinery, temporary track closures or even the potential for interfering points at the beginning or the end of tamping tasks are relevant parameters. These factors are quite difficult to integrate into an automated algorithm as their importance highly depends on the current situation and the specific goals of the user. Hence, it is more reasonable for the responsible track expert to adjust the output of the algorithm according to the abovementioned additional parameters.

However, any such adjustments will result in a deviation from the LCC optimum in the respective sections. This means the advantages of the adaption must be opposed to the increases in life cycle costs in order to achieve the optimum overall. Of course, it is also possible to include such considerations in an automated algorithm in the future. One prerequisite for this is that all data (especially cost data) are available in an appropriate way. Furthermore, this means a lot of programming effort as well as sophisticated reflections on the technical and especially economic impacts of any adaption. However, it must be stated that any automated maintenance schedule should be seen as a proposal, and a strong support for the infrastructure manager. As the track expert has the final responsibility, it must always be possible for him to validate the proposed results and to make adaptions in response to unexpected developments or not included circumstances.

By planning tamping tasks for the upcoming years, interconnections with other measures must also be considered. This is especially true in case of a fouled ballast bed that must be cleaned, or other broken components leading to a total track renewal. In these cases, a new ballast bed is installed and the boundary conditions for tamping scheduling must be adapted to the new situation. Hence, it would be a goal in the future to include further maintenance tasks into an overall planning tool. Within the tool, tasks like grinding, sleeper exchange or ballast cleaning could be implemented. Therefore, the same procedure must be applied as described in the present thesis: At first it is necessary to describe and to predict the condition of the different components in a technical way.

Afterwards, the results must be combined to reasonable section lengths for the respective task. Ultimately, it would be the aim to combine the outcomes with economic considerations within a life cycle management system. Based on this system, the tool would consider any interconnections between the different tasks and calculate the optimal point in time for re-investment on its own. Therefore, renewal tasks could also be planned by the tool autonomously. In the end, a comprehensive LCM tool would arise that proposes the necessary tasks considering all influencing boundary conditions, while also optimising life cycle costs.

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Annex

Table 25: Comparison σ_{mod}-values in areas with poor twist and for the whole line.

measuring run	# measuring points	# poor twist	% poor twist	σ_{mod} poor twist	σ_{mod} total
1	13833	21	0.2%	1.682	0.797
2	34934	272	0.8%	1.392	1.039
3	9577	21	0.2%	0.619	0.868
4	11235	3	0.0%	2.775	0.769
5	17002	74	0.4%	1.575	1.019
6	24755	316	1.3%	1.738	0.865
7	2032	28	1.4%	1.988	1.138
8	4836	0	0.0%	NA	0.66
9	31067	202	0.7%	1.825	0.921
10	15495	351	2.3%	1.753	1.209
11	7160	22	0.3%	3.08	0.825
12	17157	20	0.1%	1.596	1.004
13	11235	3	0.0%	2.775	0.769
14	9840	0	0.0%	NA	0.931
15	7995	21	0.3%	1.923	0.939
16	5746	22	0.4%	2.619	0.79
17	14793	0	0.0%	NA	0.778
18	5328	20	0.4%	1.894	0.899
19	13073	0	0.0%	NA	0.803
20	18312	63	0.3%	1.263	1.053
21	29975	52	0.2%	1.943	1.129
22	13712	326	2.4%	2.336	1.185
23	3401	22	0.6%	1.865	0.777
24	4316	21	0.5%	1.678	0.644
25	24460	44	0.2%	1.098	1.005
26	22868	622	2.7%	1.393	0.998
27	17119	23	0.1%	1.759	0.915
28	4196	21	0.5%	1.56	0.938
29	4092	20	0.5%	1.996	0.939
30	8327	150	1.8%	2.671	1.246
31	13338	450	3.4%	1.731	1.439
32	16669	395	2.4%	1.637	1.164
33	7251	96	1.3%	1.473	1.115
34	18128	179	1.0%	1.615	0.892
35	11445	51	0.4%	2.98	0.979
36	31506	4	0.0%	2.391	0.884
37	13149	600	4.6%	1.351	1.135
38	15663	71	0.5%	1.541	1.192
39	20495	741	3.6%	1.574	1.175
40	20313	542	2.7%	1.338	1.162

Table 26: Track quality parameters after tamping: <225 million gt; Q_{N1} < 0.54 mm.

		Qult1																
		0 - 0.2	0.2 - 0.4	0.4 - 0.6	0.6 - 0.8	0.8 - 1.0	1.0 - 1.2	1.2 - 1.4	1.4 - 1.6	1.6 - 1.8	1.8 - 2.0	2.0 - 2.2	2.2 - 2.4	2.4 - 2.6	2.6 - 2.8	2.8 - 3.0	>3.0	
b1	0 - 0.05	0.9719	0.9889	1.0150	1.0771	1.0758	1.0630											QN1/QN2
		0.2400	0.7089	0.8521	0.7946	0.6371	0.8060											b1/b2
		1.2946	2.4183	3.7382	5.4273	8.4277	10.9152											T1
		0.2683	1.6540	3.3044	4.9057	5.8667	9.3010											T2
		0.2073	0.6839	0.8839	0.9039	0.6961	0.8521											T2/T1
		2	389	2241	1448	213	21	0	0	0	0	0	0	0	0	0	0	n
	0.05 - 0.1		0.8877	0.9576	1.0296	0.9697	1.0069	0.9166	0.7666	0.8123	0.9235							QN1/QN2
			1.0345	1.1947	1.1635	1.0127	1.0123	0.7660	0.5827	0.8588	0.4673							b1/b2
			1.5373	2.5940	3.6791	5.5120	7.4382	9.5125	10.3045	13.2134	13.2134							T1
			1.0912	2.8306	4.4744	5.4080	7.5691	6.9000	5.0784	10.4329	5.9682							T2
			0.7098	1.0912	1.2161	0.9811	1.0176	0.7254	0.4928	0.7896	0.4517							T2/T1
		0	477	3936	5725	2624	698	239	43	1	1	0	0	0	0	0	0	n
	0.1 - 0.15		0.8221	0.9473	0.9545	0.9468	0.9253	0.8742	0.7973	0.6755	0.5298	0.5956						QN1/QN2
			1.8468	1.4134	1.2594	1.1860	1.1358	1.1402	1.0490	1.1794	0.5631	0.7139						b1/b2
			1.1669	1.6107	2.3414	3.8281	5.0662	6.4288	8.1037	9.6130	10.7503	11.8731						T1
			1.3649	2.0528	2.7410	4.3061	5.4364	6.7737	7.5004	9.3230	4.5175	6.8148						T2
			1.1698	1.2744	1.1706	1.1249	1.0731	1.0536	0.9256	0.9698	0.4202	0.5740						T2/T1
		0	135	1583	2850	2801	1607	710	235	74	48	10	0	0	0	0	0	n
	0.15 - 0.2		0.8195	0.8947	0.9950	0.9164	0.8619	0.8051	0.7714	0.8718	0.8298	0.7009						QN1/QN2
			1.4552	1.6705	1.4658	1.2364	1.2445	1.1382	1.1608	1.1956	1.1720	0.9936						b1/b2
			0.8993	1.3176	1.6361	2.7265	3.8399	5.0347	5.8615	6.8363	7.7734	8.7491						T1
			0.8581	1.8128	2.3800	3.0857	4.2759	5.0818	5.9768	7.7094	8.4908	7.6236						T2
			0.9541	1.3758	1.4547	1.1317	1.1136	1.0094	1.0197	1.1277	1.0923	0.8714						T2/T1
		0	37	413	1507	1524	1403	1080	499	171	101	21	0	0	0	0	0	n
	0.2 - 0.25		1.0188	0.8943	0.9535	0.9341	0.8725	0.8094	0.7805	0.7329	0.6931	0.7129	0.7110	0.7054				QN1/QN2
			1.6550	1.5344	1.4433	1.2855	1.2931	1.3890	1.1934	1.1294	1.2183	1.0267	1.0383	1.1037				b1/b2
			0.6172	0.9787	1.4035	2.0497	2.9514	3.8898	4.7487	5.3861	6.5179	7.2059	8.3295	8.6428				T1
			1.0505	1.2579	1.8996	2.4517	3.4383	4.7766	5.0304	5.2860	6.9083	6.5360	7.7871	8.7126				T2
			1.7020	1.2852	1.3535	1.1962	1.1650	1.2280	1.0593	0.9814	1.0599	0.9070	0.9349	1.0081				T2/T1
		0	9	149	680	987	672	640	482	278	145	35	29	1	0	0	0	n
	0.25 - 0.3		1.0024	0.7895	0.9177	0.9139	0.9451	0.8392	0.7350	0.6744	0.6804	0.6414	0.6349	0.4122	0.4125			QN1/QN2
			1.9141	1.3686	1.4742	1.2748	1.2505	1.3142	1.3351	1.2208	1.2615	1.2081	1.5059	0.8879	0.5958			b1/b2
			0.5917	0.9060	1.2029	1.7906	2.3046	3.1214	3.9914	4.5087	5.2280	5.8151	6.8268	7.1606	8.5095			T1
			1.1366	0.8515	1.5810	2.0952	2.7652	3.6879	4.5908	4.5779	5.7112	5.9545	8.9405	4.3561	3.4885			T2
			1.9209	0.9398	1.3143	1.1701	1.1998	1.1815	1.1502	1.0154	1.0924	1.0240	1.3096	0.6083	0.4100			T2/T1
		0	2	65	377	557	517	358	373	325	155	97	54	11	4	0	0	n
	0.3 - 0.35			0.7778	0.8821	0.8646	0.8289	0.8721	0.8452	0.6730	0.5393	0.5420	0.6837	0.5509	0.4454	0.3954		QN1/QN2
				1.4249	1.6327	1.2730	1.1427	1.2916	1.4524	1.3510	1.2498	1.2955	1.2509	1.2176	0.9319	0.7468		b1/b2
				0.7014	1.1574	1.5931	2.0899	2.6955	3.2402	4.0489	4.6201	5.2098	5.7574	5.9483	6.9165	7.8875		T1
				0.5948	1.6432	1.7830	2.0772	3.2277	4.3418	4.7071	4.5372	5.5549	6.4145	5.9293	4.7653	4.6577		T2
				0.8480	1.4198	1.1192	0.9939	1.1974	1.3400	1.1626	0.9821	1.0662	1.1141	0.9968	0.6890	0.5905		T2/T1
		0	0	23	192	467	404	304	329	242	169	126	61	24	7	3	0	n
	> 0.35			0.7846	0.9444	0.8476	0.7593	0.7222	0.8485	0.7273	0.5512	0.4855	0.5938	0.5544	0.3972	0.4183		QN1/QN2
				1.6885	1.5062	1.5594	1.2090	1.3017	1.5692	1.4089	1.3301	1.2536	1.3229	1.6069	0.7858	0.7294		b1/b2
				0.7708	1.0134	1.3826	1.8576	2.3618	2.9748	3.3471	4.0670	4.6207	5.0185	5.7046	6.1122	6.4216		T1
				0.9667	1.4434	1.8568	1.8432	2.5517	4.3608	4.1049	4.3504	4.5455	5.7343	7.8428	3.5597	3.5419		T2
				1.2541	1.4243	1.3430	0.9922	1.0804	1.4659	1.2264	1.0697	0.9837	1.1426	1.3748	0.5824	0.5516		T2/T1
		0	0	7	91	289	353	245	211	178	147	66	77	64	18	5	0	n

Table 27: Track quality parameters after tamping: <225 million gt; Q_{N1} 0.54 mm – 0.83 mm.

		Qult1																
		0 - 0.2	0.2 - 0.4	0.4 - 0.6	0.6 - 0.8	0.8 - 1.0	1.0 - 1.2	1.2 - 1.4	1.4 - 1.6	1.6 - 1.8	1.8 - 2.0	2.0 - 2.2	2.2 - 2.4	2.4 - 2.6	2.6 - 2.8	2.8 - 3.0	> 3.0	
b1	0 - 0.05			1.4108	1.3087	1.3605	1.2788	1.3477										QN1/QN2
				0.8115	0.7321	0.6692	0.5966	0.5291										b1/b2
				1.3322	3.5876	5.2468	8.5933	10.5088										T1
				5.0479	5.1936	6.3924	7.1309	7.7981										T2
				3.7892	1.4476	1.2183	0.8298	0.7421										T2/T1
		0	0	50	763	816	286	39	0	0	0	0	0	0	0	0	0	n
	0.05 - 0.1			1.3835	1.3005	1.2983	1.2391	1.1565	1.1505	1.1980	0.9912							QN1/QN2
				0.6473	1.0228	0.9768	0.9475	0.8318	0.8191	0.7161	0.4812							b1/b2
				0.8094	2.1924	3.2444	5.1578	7.2075	8.5253	9.8316	11.0168							T1
				2.0018	4.1463	5.0564	6.4888	6.9388	7.8932	8.0070	5.2693							T2
				2.4731	1.8912	1.5585	1.2581	0.9627	0.9258	0.8144	0.4783							T2/T1
		0	0	13	1912	4085	2444	1028	308	122	11	0	0	0	0	0	0	n
	0.1 - 0.15				1.2657	1.2614	1.2103	1.0907	1.0517	0.9792	0.8839	1.0394	1.2095					QN1/QN2
					1.1186	1.1273	1.1064	0.9768	1.0517	0.9567	0.7085	0.8680	0.9033					b1/b2
					1.4068	2.3143	3.3819	4.9150	6.1866	7.7598	9.0798	9.9826	10.8310					T1
					2.7133	3.8448	4.7830	5.2347	6.7870	7.3134	5.9256	8.8468	10.6414					T2
					1.9287	1.6614	1.4143	1.0650	1.0971	0.9425	0.6526	0.8862	0.9825					T2/T1
		0	0	0	847	3169	3103	1889	866	470	219	80	19	0	0	0	0	n
	0.15 - 0.2				1.2233	1.1662	1.1304	1.0766	1.0848	0.9964	0.9020	0.9110	0.8282	0.9113	0.9102			QN1/QN2
					1.4670	1.2435	1.1454	1.1759	1.0957	1.0953	1.1909	0.8950	0.9291	0.9653	0.9537			b1/b2
					1.1291	1.6713	2.6343	3.5702	4.6257	5.5414	6.8612	8.3579	8.9019	9.1385	9.0584			T1
					2.5582	2.7332	3.5193	4.5213	5.4104	6.0542	7.6703	7.1224	7.5225	8.4259	8.2508			T2
					2.2656	1.6354	1.3360	1.2664	1.1696	1.0925	1.1179	0.8522	0.8450	0.9220	0.9108			T2/T1
		0	0	0	308	1599	2114	1846	1194	690	277	137	41	30	4	0	0	n
	0.2 - 0.25				1.1315	1.1950	1.1265	1.1152	1.0422	0.9692	0.8915	0.8971	0.9840	0.7527	0.8192	0.6047		QN1/QN2
					1.6352	1.3546	1.2676	1.2270	1.0635	1.1101	1.0507	1.2606	1.3276	1.0919	0.5763	0.9461		b1/b2
					1.0198	1.4508	2.0363	2.8111	3.5382	4.3032	5.1037	6.0951	6.3703	7.7738	9.2919	7.9696		T1
					2.1632	2.5893	3.0011	3.8350	3.8974	4.6639	4.9806	7.2578	8.3876	7.2979	4.8372	5.4918		T2
					2.1212	1.7847	1.4739	1.3642	1.1015	1.0838	0.9759	1.1908	1.3167	0.9388	0.5206	0.6891		T2/T1
		0	0	0	104	757	1177	1332	1053	701	372	172	49	22	1	2	0	n
	0.25 - 0.3				1.2326	1.2095	1.1434	1.1315	1.0528	0.9525	0.9423	0.9049	0.8313	0.9257	0.7556	0.5926		QN1/QN2
					1.5309	1.3775	1.1862	1.2887	1.2955	1.2185	1.2287	1.1840	1.0962	1.2932	1.2851	0.9603		b1/b2
					0.8379	1.1554	1.7044	2.2711	2.8908	3.5844	4.2892	5.0505	5.8839	6.6595	6.7029	7.9659		T1
					1.8969	2.1177	2.3703	3.3007	3.9104	4.2129	5.0773	5.6588	5.8883	8.3071	7.5100	5.5248		T2
					2.2640	1.8329	1.3907	1.4533	1.3527	1.1754	1.1838	1.1204	1.0008	1.2474	1.1204	0.6936		T2/T1
		0	0	0	18	371	682	889	715	611	359	197	80	24	31	10	0	n
	0.3 - 0.35				1.2601	1.0772	1.1573	1.0597	1.0542	1.0386	0.9734	0.9867	0.7923	0.7408	0.7356	0.7934	0.7844	QN1/QN2
					1.4852	1.6915	1.4885	1.4122	1.2741	1.3767	1.4520	1.2078	0.9961	0.8702	1.0209	0.6882	1.0870	b1/b2
					0.7805	1.1246	1.4280	2.0015	2.4534	3.0573	3.7536	4.3253	4.7943	5.5588	5.9997	6.3347	7.2658	T1
					1.6917	2.1198	2.5272	2.9941	3.2641	4.3224	5.3665	5.1886	4.2183	4.1579	5.4239	3.9558	7.2327	T2
					2.1674	1.8850	1.7698	1.4960	1.3304	1.4138	1.4297	1.1996	0.8799	0.7480	0.9040	0.6245	0.9954	T2/T1
		0	0	0	4	204	448	548	541	437	240	244	123	72	39	16	14	n
	> 0.35					1.0693	1.1355	1.0271	0.9510	0.9966	1.0368	0.9504	0.9664	0.9440	0.8048	0.8264	0.7070	QN1/QN2
						1.9461	1.4878	1.5021	1.5225	1.3045	1.3497	1.4203	1.2393	1.6735	1.3083	1.2420	0.7349	b1/b2
						0.8973	1.1504	1.8041	2.1893	2.7066	3.1174	3.8105	4.3962	4.7347	5.1610	5.6838	5.9027	T1
						1.9446	2.0324	2.7801	3.1859	3.5226	4.3000	5.2770	5.3686	7.7338	6.1767	6.5644	3.7677	T2
						2.1673	1.7668	1.5410	1.4552	1.3015	1.3794	1.3849	1.2212	1.6334	1.1968	1.1549	0.6383	T2/T1
		0	0	0	0	89	274	334	378	370	257	227	173	88	45	26	17	n

Table 28: Track quality parameters after tamping:

<225 million gt; Q_{N1} > 0.83 mm.

		Qult1															
b1		0 - 0.2	0.2 - 0.4	0.4 - 0.6	0.6 - 0.8	0.8 - 1.0	1.0 - 1.2	1.2 - 1.4	1.4 - 1.6	1.6 - 1.8	1.8 - 2.0	2.0 - 2.2	2.2 - 2.4	2.4 - 2.6	2.6 - 2.8	2.8 - 3.0	> 3.0
0 - 0.05	QN1/QN2					1.6852	1.7433	1.6839	1.7686	2.4065	3.0561	3.1348	3.4867				
	b1/b2					0.5652	0.5494	0.5019	0.5987	0.3774	0.4255	0.2336	0.1443				
	T1					2.1827	3.7498	5.3764	6.3259	6.8934	1.0806	0.9184	1.1230				
	T2					6.0216	7.6187	7.6492	10.4455	9.9253	12.5649	7.0781	11.2357				
	T2/T1					2.7587	2.0317	1.4227	1.6512	1.4398	11.6277	7.7070	10.0050				
	n	0	0	0	0	86	221	141	55	6	3	3	3	0	0	0	0
0.05 - 0.1	QN1/QN2					1.5222	1.5450	1.6245	1.4563	1.4397	1.4159	1.5201	1.6660	1.7346	2.2032		
	b1/b2					0.8494	0.9560	0.9232	0.8186	0.6986	0.6276	0.7884	0.7384	0.4825	1.1601		
	T1					1.5090	2.5431	3.5529	4.9351	6.0399	6.7934	8.3417	4.3897	5.4817	8.3116		
	T2					4.8032	6.3798	7.7135	7.2499	7.1473	6.9818	10.4122	9.4955	6.8592	21.7066		
	T2/T1					3.1831	2.5087	2.1711	1.4690	1.1833	1.0277	1.2482	2.1631	1.2513	2.6116		
	n	0	0	0	0	233	997	1176	862	486	183	61	17	7	7	0	0
0.1 - 0.15	QN1/QN2					1.7863	1.5176	1.4946	1.5025	1.4075	1.5224	1.4346	1.3317	1.8830	1.1897	0.8641	1.5672
	b1/b2					1.0565	1.0784	1.0334	0.9811	0.9772	0.9196	0.8871	0.7399	0.7712	0.6750	0.4572	0.5131
	T1					1.0824	1.7760	2.5124	3.5585	4.5770	4.9258	5.3844	5.8969	4.1343	8.5258	7.7954	1.4457
	T2					4.5928	4.6114	5.3250	6.2548	6.8851	7.6578	7.6502	6.5436	8.1032	6.8971	2.5950	4.5912
	T2/T1					4.2430	2.5965	2.1195	1.7577	1.5043	1.5546	1.4208	1.1097	1.9600	0.8090	0.3329	3.1757
	n	0	0	0	0	88	978	1498	1836	1232	759	439	160	58	9	24	10
0.15 - 0.2	QN1/QN2					1.4032	1.5579	1.4726	1.3992	1.4173	1.4283	1.4578	1.4150	1.4837	2.1220	2.1174	0.8799
	b1/b2					1.2669	1.1431	1.1387	1.0801	1.0241	1.1155	0.9254	0.9279	0.7847	0.6525	0.7416	0.6423
	T1					0.8144	1.3339	1.9830	2.7199	3.2742	3.8613	4.3961	5.3333	5.3213	4.0971	4.6440	8.3527
	T2					2.8455	3.7205	4.2863	4.7752	5.2723	6.5698	6.2503	7.0634	6.5317	6.3630	8.3820	4.5419
	T2/T1					3.4942	2.7892	2.1615	1.7556	1.6102	1.7015	1.4218	1.3244	1.2275	1.5531	1.8049	0.5438
	n	0	0	0	0	18	571	1197	1565	1434	991	644	440	215	117	46	24
0.2 - 0.25	QN1/QN2					1.8180	1.5733	1.4184	1.3209	1.3824	1.3786	1.3296	1.4037	1.3163	1.2921	1.7986	1.5931
	b1/b2					1.9074	1.1801	1.2571	1.1909	1.1274	1.1016	1.0915	0.9777	1.0915	0.9425	1.1930	0.8858
	T1					0.6928	1.1027	1.6302	2.3564	2.6713	3.0591	3.8716	4.2002	4.4511	4.7517	3.4787	3.5248
	T2					4.6734	3.0178	3.6720	4.0898	4.5665	5.0162	5.6560	5.7756	6.6064	5.9124	8.9929	6.6477
	T2/T1					6.7452	2.7367	2.2525	1.7356	1.7094	1.6398	1.4609	1.3751	1.4842	1.2443	2.5851	1.8860
	n	0	0	0	0	9	309	721	1112	1364	1100	869	483	315	156	51	26
0.25 - 0.3	QN1/QN2						1.5487	1.4535	1.2730	1.2850	1.2866	1.4367	1.3650	1.4618	1.4182	1.3939	1.3354
	b1/b2						1.3304	1.2530	1.1357	1.1064	1.1247	1.0630	0.9248	0.9723	1.0545	0.8958	1.1299
	T1						1.0167	1.4037	2.0337	2.3223	2.7358	3.0100	3.5628	3.4225	4.0920	4.0865	4.2853
	T2						2.9081	3.1138	3.1694	3.5269	4.1139	4.6780	4.4776	5.0029	6.0925	5.2963	6.7715
	T2/T1						2.8602	2.2184	1.5585	1.5187	1.5037	1.5541	1.2567	1.4618	1.4889	1.2960	1.5802
	n	0	0	0	0	0	162	401	724	991	918	735	554	299	240	118	99
0.3 - 0.35	QN1/QN2						1.4806	1.3688	1.3479	1.2541	1.3714	1.3409	1.2293	1.3218	1.5260	1.5159	1.2122
	b1/b2						1.7218	1.2694	1.1924	1.2025	1.1275	1.1489	1.0632	1.0601	1.1524	1.0877	0.8994
	T1						0.7932	1.1158	1.6622	2.0957	2.2801	2.7507	3.3366	3.3645	3.4164	3.9886	4.5644
	T2						2.9046	2.4308	2.9307	3.3012	3.6519	4.2572	4.2785	4.6564	5.8164	6.1048	4.9210
	T2/T1						3.6617	2.1786	1.7631	1.5752	1.6016	1.5477	1.2823	1.3840	1.7025	1.5306	1.0781
	n	0	0	0	0	0	70	236	469	682	729	790	625	462	227	145	96
> 0.35	QN1/QN2						1.6743	1.1946	1.5110	1.1717	1.2897	1.2842	1.2862	1.3402	1.2540	1.1742	1.2410
	b1/b2						1.9436	1.2911	1.3073	1.2011	1.1996	1.1543	1.2397	1.0439	0.9680	1.1870	1.0463
	T1						0.7675	1.0647	1.3867	1.8874	2.1881	2.4514	2.8053	3.0697	3.2913	4.1985	3.7935
	T2						3.3543	1.9003	3.0033	2.7471	3.4168	3.6379	4.3807	4.1636	3.9395	5.6099	4.9230
	T2/T1						4.3707	1.7848	2.1659	1.4555	1.5616	1.4840	1.5615	1.3563	1.1969	1.3362	1.2977
	n	0	0	0	0	0	27	186	306	401	541	577	491	367	311	151	74

Table 29: Track quality parameters after tamping:

225 - 475 million gt; Q_{N1} < 0.54 mm.

b1		Qult1																
		0 - 0.2	0.2 - 0.4	0.4 - 0.6	0.6 - 0.8	0.8 - 1.0	1.0 - 1.2	1.2 - 1.4	1.4 - 1.6	1.6 - 1.8	1.8 - 2.0	2.0 - 2.2	2.2 - 2.4	2.4 - 2.6	2.6 - 2.8	2.8 - 3.0	> 3.0	
	0 - 0.05		0.9638	1.0128	1.1399	1.2107	1.0738											QN1/QN2
			0.6024	0.7725	0.7142	0.6116	0.5909											b1/b2
			2.6939	4.4777	6.4586	8.6418	10.7415											T1
			1.4230	3.5472	5.5145	6.4299	6.7356											T2
			0.5282	0.7922	0.8538	0.7440	0.6271											T2/T1
		0	78	826	850	177	3	0	0	0	0	0	0	0	0	0	0	n
	0.05 - 0.1		0.9610	0.9240	1.0044	0.9031	0.9848	0.8863	0.8319	0.9906								QN1/QN2
			1.1335	0.9609	0.9643	0.8122	0.7693	0.7208	0.8715	0.7051								b1/b2
			1.2094	2.6367	3.6205	5.8683	7.7748	9.1344	10.1798	11.7943								T1
			1.2104	2.1345	3.5160	4.2601	5.9130	6.0957	7.9268	8.2812								T2
			1.0008	0.8095	0.9711	0.7260	0.7605	0.6673	0.7787	0.7021								T2/T1
		0	96	1276	2845	1790	899	287	47	3	0	0	0	0	0	0	0	n
	0.1 - 0.15		0.7848	0.9831	0.9551	0.9149	0.8549	0.7583	0.6384	0.7277	0.9158	0.6931						QN1/QN2
			1.0034	1.2971	1.0641	0.9660	0.9813	0.8542	0.7197	0.7741	1.0576	0.9479						b1/b2
			1.0792	1.6358	2.4892	3.7124	5.2268	6.9324	8.1741	8.9503	9.5328	11.9813						T1
			0.4544	2.0569	2.4772	3.2468	4.5216	4.9594	4.5485	5.9686	9.7284	10.0485						T2
			0.4211	1.2575	0.9952	0.8746	0.8651	0.7154	0.5565	0.6669	1.0205	0.8387						T2/T1
		0	27	460	1745	1562	957	797	452	170	22	3	0	0	0	0	0	n
	0.15 - 0.2		1.1538	1.0176	0.9751	0.9467	0.9533	0.8080	0.6947	0.6750	0.6986	0.7636	0.7008	0.4306	0.7916			QN1/QN2
			1.4233	0.9984	1.0643	1.1098	1.0202	1.0319	1.0274	0.9500	0.8973	0.9849	0.8290	1.0694	1.0539			b1/b2
			0.9152	1.0857	1.7895	2.6393	3.7675	4.8633	6.3045	7.2012	8.4088	8.6165	10.2948	12.2731	11.8691			T1
			1.6041	1.1185	1.8358	2.7679	3.7097	4.3553	5.4046	5.8121	6.5013	7.6902	7.6747	11.2946	11.9336			T2
			1.7527	1.0302	1.0259	1.0487	0.9847	0.8955	0.8573	0.8071	0.7732	0.8925	0.7455	0.9203	1.0054			T2/T1
		0	5	221	652	936	591	495	387	304	138	70	25	4	8	0	0	n
	0.2 - 0.25			1.1562	0.9534	0.8662	0.9135	0.8259	0.7159	0.5331	0.5567	0.5416	0.6543	0.4929	0.5015			QN1/QN2
				1.3886	1.2368	1.1091	1.1339	1.0291	1.1498	1.0248	0.9423	1.1100	1.7807	0.8668	1.1361			b1/b2
				0.9493	1.2016	2.2950	2.8684	3.8479	4.5453	6.5079	6.8783	7.7348	8.7990	8.7301	11.7911			T1
				1.6097	1.3702	2.2080	3.0504	3.5399	4.2612	5.1940	5.1026	6.9898	13.9928	6.1439	11.9804			T2
				1.6957	1.1403	0.9621	1.0635	0.9199	0.9375	0.7981	0.7418	0.9037	1.5903	0.7038	1.0161			T2/T1
		0	0	122	262	510	411	286	200	176	160	77	34	24	9	0	0	n
	0.25 - 0.3			1.0328	1.0645	0.8582	0.8381	0.9007	0.7310	0.6401	0.6985	0.5583	0.5039	0.4524	0.4514	0.6272	0.5722	QN1/QN2
				1.6417	1.2022	1.1488	1.0185	1.1102	1.0487	1.2116	0.9865	0.9449	1.0389	0.8026	0.7212	0.9097	0.6789	b1/b2
				0.8630	0.9958	1.7537	2.7136	3.0649	3.8017	4.4244	5.3516	6.2450	6.8931	7.2994	8.7309	8.7749	9.5238	T1
				1.4812	1.3101	1.7130	2.4866	3.1963	3.3723	4.2175	4.5946	4.9003	5.7351	4.4161	4.8432	7.1132	5.6906	T2
				1.7163	1.3155	0.9768	0.9163	1.0429	0.8871	0.9532	0.8586	0.7847	0.8320	0.6050	0.5547	0.8106	0.5975	T2/T1
		0	0	42	195	213	264	228	143	113	42	70	49	22	7	13	7	n
	0.3 - 0.35			0.9728	1.1850	0.9642	0.9214	0.9466	0.8032	0.7588	0.8216	0.5591	0.5558	0.4927	0.3804	0.5755	0.5180	QN1/QN2
				1.1672	1.2960	1.0560	0.9960	1.1014	1.2347	1.1470	1.1247	0.9262	1.0536	1.0700	0.6280	1.6111	1.5175	b1/b2
				0.9341	0.9517	1.3398	2.0824	2.6759	3.2046	3.8768	4.0980	5.2801	5.7407	6.4913	7.2767	8.0348	8.0643	T1
				1.0604	1.4901	1.3595	1.9650	2.8661	3.5107	3.9302	4.2588	3.9879	5.1519	5.5255	3.5682	11.4342	10.6528	T2
				1.1352	1.5657	1.0147	0.9436	1.0711	1.0955	1.0138	1.0392	0.7553	0.8974	0.8512	0.4904	1.4231	1.3210	T2/T1
		0	0	7	165	151	123	201	149	93	60	56	33	38	25	3	6	n
	> 0.35			0.9096	0.9737	1.1324	0.8002	0.8884	0.8347	0.8078	0.7868	0.7867	0.6557	0.4714	0.4721	0.2847	0.3581	QN1/QN2
				1.1679	1.3344	1.3320	1.1034	1.2046	1.2003	1.2151	1.1708	0.9989	1.0498	1.4054	2.2813	1.1576	0.5843	b1/b2
				0.9250	1.0038	1.1011	1.9694	2.4136	2.8064	3.2323	3.9132	4.2377	5.3008	5.5802	6.1446	6.8051	6.9604	T1
				1.0002	1.3043	1.6570	1.8777	2.7369	3.0940	3.5644	4.1621	3.8688	4.9574	6.1427	11.5334	5.5559	3.0038	T2
				1.0812	1.2994	1.5049	0.9534	1.1340	1.1025	1.1027	1.0636	0.9129	0.9352	1.1008	1.8770	0.8164	0.4316	T2/T1
		0	0	1	68	108	98	126	141	117	83	60	12	17	16	10	3	n

Table 30: Track quality parameters after tamping:

225 - 475 million gt; Q_{N1} 0.54 mm – 0.83 mm.

		Qult1															
b1		0 - 0.2	0.2 - 0.4	0.4 - 0.6	0.6 - 0.8	0.8 - 1.0	1.0 - 1.2	1.2 - 1.4	1.4 - 1.6	1.6 - 1.8	1.8 - 2.0	2.0 - 2.2	2.2 - 2.4	2.4 - 2.6	2.6 - 2.8	2.8 - 3.0	> 3.0
0 - 0.05	QN1/QN2			1.5732	1.2661	1.2757	1.2160	1.9415									
	b1/b2			0.7340	0.6094	0.6081	0.6438	0.7856									
	T1			1.2557	3.9447	5.2407	8.4214	11.3219									
	T2			4.6308	4.2368	5.2241	7.0004	15.8313									
	T2/T1			3.6879	1.0740	0.9968	0.8313	1.3983									
	n	0	0	5	165	332	82	12	0	0	0	0	0	0	0	0	0
0.05 - 0.1	QN1/QN2			1.1735	1.2106	1.1759	1.2052	1.1320	1.1239	1.4607							
	b1/b2			0.5538	0.8899	0.8397	0.8317	0.7337	0.7153	0.9642							
	T1			0.8104	2.0196	3.5604	5.0834	7.1861	9.1665	11.1136							
	T2			1.2382	3.0130	4.0315	5.4067	5.9621	7.1664	12.7949							
	T2/T1			1.5278	1.4919	1.1323	1.0636	0.8297	0.7818	1.1513							
	n	0	0	4	687	1729	1120	651	176	38	0	0	0	0	0	0	0
0.1 - 0.15	QN1/QN2			1.5931	1.1390	1.0885	1.0706	1.0483	0.9217	0.8370	0.8681	0.9821	0.9652				
	b1/b2			0.7821	0.9835	0.9904	0.8871	0.9286	0.7404	0.6963	0.6734	0.7416	0.6946				
	T1			0.5128	1.4682	2.2891	3.6022	4.6798	6.5769	7.6534	8.7494	10.3637	10.6481				
	T2			1.8606	2.0645	2.6801	3.5121	4.5804	4.5163	4.6185	5.3429	7.6232	7.2794				
	T2/T1			3.6282	1.4061	1.1708	0.9750	0.9788	0.6867	0.6035	0.6107	0.7356	0.6836				
	n	0	0	1	268	1275	1629	943	565	341	124	51	2	0	0	0	0
0.15 - 0.2	QN1/QN2				1.1872	1.0382	1.0987	1.0747	0.9572	0.8686	0.8210	0.6345	0.7521	1.2656	0.6643		
	b1/b2				1.4043	1.0897	1.0602	0.9975	0.9164	0.8142	0.7544	0.5985	0.7061	1.5054	0.3611		
	T1				1.0465	1.9236	2.5139	3.4102	4.4178	5.9807	7.0406	7.8354	9.4320	9.7165	10.1012		
	T2				2.1750	2.2392	3.0315	3.6805	3.8862	4.4003	4.6664	3.3642	5.7750	15.9876	2.8913		
	T2/T1				2.0783	1.1641	1.2059	1.0793	0.8797	0.7358	0.6628	0.4294	0.6123	1.6454	0.2862		
	n	0	0	0	102	693	1097	973	649	368	277	109	56	22	3	0	0
0.2 - 0.25	QN1/QN2				1.1729	1.2494	1.0314	1.0688	1.0469	0.8654	0.8687	0.8937	0.7897	1.1105	1.0824	0.7977	
	b1/b2				1.4306	1.3644	1.1673	1.0988	1.0015	0.8468	1.0317	0.9343	0.8078	0.8673	1.1381	0.6459	
	T1				0.9753	1.3476	2.1087	2.7301	3.5776	4.2920	5.6046	6.0566	6.9536	8.1785	8.5576	9.5896	
	T2				1.9447	2.6109	2.5664	3.2203	3.7235	3.2078	5.2985	5.3082	4.9778	7.3577	9.9836	5.8150	
	T2/T1				1.9940	1.9374	1.2171	1.1796	1.0408	0.7474	0.9454	0.8764	0.7159	0.8996	1.1666	0.6064	
	n	0	0	0	32	289	669	718	498	334	169	138	67	16	7	5	0
0.25 - 0.3	QN1/QN2				1.3545	1.2803	1.0824	1.0768	1.1331	0.9535	0.9293	0.8527	0.7915	0.8289	0.2514	0.8227	0.7797
	b1/b2				0.9932	1.3626	1.0916	1.1087	1.0935	0.9926	0.8349	0.7314	0.9136	1.3150	0.8175	0.8208	0.6216
	T1				0.8347	1.1431	1.7578	2.1887	2.9185	3.6234	4.1849	5.0237	5.8753	6.2267	7.0398	7.9602	9.5332
	T2				1.3536	2.2245	2.1175	2.6286	3.5264	3.4749	3.3259	3.3709	4.7962	7.4946	0.3727	6.0996	5.5291
	T2/T1				1.6217	1.9459	1.2047	1.2010	1.2083	0.9590	0.7947	0.6710	0.8163	1.2036	0.0529	0.7663	0.5800
	n	0	0	0	16	170	347	603	454	332	137	109	110	35	6	10	4
0.3 - 0.35	QN1/QN2				1.1116	1.1738	1.0976	1.0163	1.0171	1.1283	0.9863	0.8282	0.8124	0.8654	0.7307	0.6992	0.8715
	b1/b2				2.4889	1.3641	1.3748	1.0742	1.1486	1.0690	0.9894	0.8963	1.1209	1.5062	1.4029	0.7812	0.7398
	T1				0.4766	0.9514	1.4347	2.0591	2.4358	3.0209	3.7817	4.4700	4.8603	5.4785	5.9451	6.2580	7.8361
	T2				1.7042	1.6849	2.2262	2.2464	2.8395	3.4904	3.7140	3.6113	4.9155	7.7420	7.2232	4.1511	5.5313
	T2/T1				3.5757	1.7710	1.5517	1.0910	1.1657	1.1554	0.9821	0.8079	1.0114	1.4132	1.2150	0.6633	0.7059
	n	0	0	0	1	82	165	352	330	286	148	110	71	41	11	4	2
> 0.35	QN1/QN2				1.0228	1.2503	1.1100	0.9854	0.9908	1.2740	0.9880	0.8720	0.8800	0.8665	0.8877	0.7061	0.6625
	b1/b2				2.5196	1.3414	1.2318	1.1756	1.2190	1.1940	1.1267	0.9083	1.0881	1.2069	0.7612	0.9552	0.8409
	T1				0.5320	0.7957	1.0826	1.8107	2.1711	2.7340	2.9633	3.8724	4.1645	4.7476	5.4959	6.1344	6.1489
	T2				1.4281	1.5108	1.5596	2.0967	2.6256	3.7255	3.3136	3.2936	4.2468	5.3754	3.9897	5.2055	4.3603
	T2/T1				2.6846	1.8987	1.4406	1.1580	1.2093	1.3627	1.1182	0.8505	1.0198	1.1322	0.7259	0.8486	0.7091
	n	0	0	0	4	50	98	137	246	222	114	88	103	28	10	6	16

Table 31: Track quality parameters after tamping:

225 - 475 million gt; Q_{N1} > 0.83 mm.

		Qult1																
b1		0 - 0.2	0.2 - 0.4	0.4 - 0.6	0.6 - 0.8	0.8 - 1.0	1.0 - 1.2	1.2 - 1.4	1.4 - 1.6	1.6 - 1.8	1.8 - 2.0	2.0 - 2.2	2.2 - 2.4	2.4 - 2.6	2.6 - 2.8	2.8 - 3.0	> 3.0	
	0 - 0.05					1.3691	1.6165	1.5412	1.4822	1.9250	2.0651	2.5999						QN1/QN2
						0.4463	0.4624	0.5232	0.3433	0.8891	0.8769	0.5353						b1/b2
						1.8373	4.5422	6.7762	8.5350	7.3454	7.3478	1.1721						T1
						3.3731	5.9489	7.1826	5.6795	20.7982	20.9130	14.4237						T2
						1.8359	1.3097	1.0600	0.6654	2.8315	2.8462	12.3059						T2/T1
		0	0	0	0	24	61	28	11	11	1	1	0	0	0	0	0	n
	0.05 - 0.1					1.3374	1.4380	1.3854	1.3151	1.2047	1.4865	1.8340	2.4567	1.6313	1.4354			QN1/QN2
						0.5550	0.8879	0.7509	0.5814	0.5720	0.5788	0.6230	0.7277	0.2416	0.1724			b1/b2
						1.7578	2.7098	3.7669	5.5587	6.3870	9.7253	4.8084	1.1842	1.1721	0.9489			T1
						2.6415	5.3002	5.3583	4.9791	4.8637	8.1936	8.0659	11.4208	2.6923	1.7488			T2
						1.5027	1.9559	1.4225	0.8957	0.7615	0.8425	1.6774	9.6440	2.2969	1.8429			T2/T1
		0	0	0	0	60	334	393	274	110	70	15	4	1	2	0	0	n
	0.1 - 0.15					1.1845	1.3740	1.1861	1.2145	1.1848	1.3364	1.4654	1.5830	1.9887	1.3641			QN1/QN2
						0.8050	0.9328	0.8814	0.9396	0.8076	0.7309	0.7614	0.7904	0.9025	0.3308			b1/b2
						1.2130	1.9711	3.0982	3.9820	4.7712	5.1217	6.0929	7.8719	2.6633	1.6680			T1
						1.8620	3.7060	3.7259	4.9982	4.8747	5.5298	7.0663	9.3588	9.6248	2.3321			T2
						1.5350	1.8801	1.2026	1.2552	1.0217	1.0797	1.1598	1.1889	3.6139	1.3982			T2/T1
		0	0	0	0	19	263	688	579	462	235	121	27	6	4	0	0	n
	0.15 - 0.2					1.8834	1.2610	1.0939	1.0878	1.0969	1.1172	1.0670	1.0560	0.8059	1.0215	1.4145	1.1581	QN1/QN2
						0.8978	0.9793	0.9393	0.8957	0.9550	0.8002	0.7040	0.6947	0.4971	0.4578	0.5761	0.9549	b1/b2
						0.6920	1.5129	2.3285	3.1937	3.7897	4.2066	5.2478	6.4506	7.0566	7.9166	1.7672	12.0775	T1
						2.6994	2.5413	2.6046	3.2532	4.0888	3.9011	3.9629	4.7178	2.7424	3.6916	3.2225	12.2659	T2
						3.9006	1.6797	1.1186	1.0186	1.0789	0.9274	0.7551	0.7314	0.3886	0.4663	1.8235	1.0156	T2/T1
		0	0	0	0	6	213	616	660	688	469	308	177	57	13	2	1	n
	0.2 - 0.25					1.5748	1.1727	1.1491	1.1252	1.1071	1.0695	1.0355	1.1706	0.9178	0.9851	1.1746	1.4131	QN1/QN2
						1.0127	1.0182	1.0119	1.0134	0.9742	0.9256	0.9908	0.8758	0.6526	0.9170	0.7541	0.7496	b1/b2
						0.4817	1.1517	1.7927	2.4115	2.9156	3.6221	4.3298	4.4821	5.6163	5.7374	5.6270	4.7563	T1
						1.9827	1.7704	2.3528	2.9376	3.2837	3.6406	4.4657	4.6332	3.3733	5.1798	4.9746	5.3000	T2
						4.1161	1.5372	1.3125	1.2181	1.1263	1.0051	1.0314	1.0337	0.6006	0.9028	0.8841	1.1143	T2/T1
		0	0	0	0	1	88	347	559	630	456	371	252	89	45	30	14	n
	0.25 - 0.3					1.0958	1.1521	1.0957	1.0896	1.0924	1.0532	1.1541	1.1824	1.0692	0.8981	1.2095	1.0762	QN1/QN2
						3.4371	1.0786	1.0224	1.0787	0.9802	1.0416	0.9129	0.8511	0.9933	0.6324	0.6183	0.8658	b1/b2
						0.4398	0.9787	1.5160	2.0064	2.3261	2.9667	3.2437	3.6357	4.8108	5.7239	4.5849	4.4740	T1
						2.3884	1.5201	1.8538	2.4717	2.6016	3.2979	3.4966	3.6955	5.0488	3.3084	3.4608	4.2710	T2
						5.4308	1.5531	1.2229	1.2320	1.1184	1.1116	1.0780	1.0165	1.0495	0.5780	0.7548	0.9546	T2/T1
		0	0	0	0	2	37	234	550	533	417	386	188	113	74	44	20	n
	0.3 - 0.35					0.9174	1.4164	1.1784	1.0712	1.1201	1.0652	1.0282	1.1536	1.1394	0.9384	0.9832	1.1961	QN1/QN2
						2.4636	1.4951	1.2074	1.1126	1.0802	0.9513	0.9337	0.8707	0.9446	0.7053	0.8975	0.7537	b1/b2
						0.4399	0.8471	1.2529	1.8303	2.1192	2.5070	2.8678	3.0099	3.6376	4.4676	5.0973	4.0431	T1
						0.4775	2.4679	2.0377	2.2493	2.6564	2.5769	2.7702	3.0717	3.8966	2.9824	4.5168	3.7135	T2
						1.0853	2.9134	1.6264	1.2289	1.2535	1.0279	0.9660	1.0205	1.0712	0.6676	0.8861	0.9185	T2/T1
		0	0	0	0	3	27	117	379	469	538	415	284	157	116	62	28	n
	> 0.35						0.9929	1.0637	1.1759	1.0047	1.1181	1.1653	1.0545	1.1110	1.0580	1.0363	1.0769	QN1/QN2
							1.3448	1.2452	1.2424	1.1892	1.1177	1.0916	0.9088	0.9345	0.8281	0.8558	1.2913	b1/b2
							0.8710	1.2069	1.4561	1.9562	2.1231	2.2453	2.6628	2.9007	3.2954	4.0263	4.6301	T1
							1.1485	1.6822	2.2999	2.3410	2.7263	2.9666	2.5845	3.0645	2.8968	3.5518	6.3034	T2
							1.3187	1.3939	1.5795	1.1967	1.2841	1.3213	0.9706	1.0565	0.8790	0.8821	1.3614	T2/T1
		0	0	0	0	0	13	59	172	356	386	339	259	226	97	59	42	n

Table 32: Track quality parameters after tamping:

> 475 million gt; Q_{N1} < 0.54 mm.

		Qult1															
		0 - 0.2	0.2 - 0.4	0.4 - 0.6	0.6 - 0.8	0.8 - 1.0	1.0 - 1.2	1.2 - 1.4	1.4 - 1.6	1.6 - 1.8	1.8 - 2.0	2.0 - 2.2	2.2 - 2.4	2.4 - 2.6	2.6 - 2.8	2.8 - 3.0	> 3.0
b1																	
0 - 0.05	QN1/QN2		1.1238	1.1499	1.0502	0.8677	0.9452										
	b1/b2		0.4079	0.6334	0.5346	0.4746	0.7523										
	T1		4.2038	4.2382	6.2587	9.7377	11.7745										
	T2		2.0372	3.3822	3.5813	3.9422	8.4139										
	T2/T1		0.4846	0.7980	0.5722	0.4048	0.7146										
	n	0	7	104	123	24	3	0	0	0	0	0	0	0	0	0	0
0.05 - 0.1	QN1/QN2		1.0927	0.9574	1.0163	1.1384	1.4394	0.4586									
	b1/b2		0.9464	0.7784	0.8087	0.7911	0.6059	0.3367									
	T1		1.4525	2.6904	3.9953	4.9741	8.7604	11.6371									
	T2		1.7042	1.9339	3.3037	4.5348	6.3654	2.4445									
	T2/T1		1.1733	0.7188	0.8269	0.9117	0.7266	0.2101									
	n	0	15	251	556	252	30	5	0	0	0	0	0	0	0	0	0
0.1 - 0.15	QN1/QN2		0.9301	0.9592	0.8792	1.0164	0.9976	1.0497	0.9228								
	b1/b2		1.5381	1.4721	1.3464	0.9889	0.7994	0.8629	0.7040								
	T1		1.0772	1.4108	2.6234	3.4447	4.9127	5.5557	7.0228								
	T2		1.4040	1.9105	2.9020	3.4684	3.9198	4.9500	4.7151								
	T2/T1		1.3034	1.3541	1.1062	1.0069	0.7979	0.8910	0.6714								
	n	0	21	161	287	292	91	27	3	0	0	0	0	0	0	0	0
0.15 - 0.2	QN1/QN2		0.9674	1.1465	1.1758	0.9603	0.6664	0.7259	0.5347	0.6535							
	b1/b2		0.5841	1.5502	1.2790	0.9043	0.9552	0.8776	0.5816	1.2212							
	T1		0.8333	1.0275	1.4839	2.6091	3.3677	4.3427	5.4651	6.3654							
	T2		0.4579	2.0035	2.3402	2.2591	1.9582	2.9666	1.7142	6.1028							
	T2/T1		0.5495	1.9499	1.5770	0.8658	0.5815	0.6831	0.3137	0.9587							
	n	0	1	124	157	80	74	24	6	10	0	0	0	0	0	0	0
0.2 - 0.25	QN1/QN2			1.1843	1.3877	0.8130	0.8632	0.6932	0.9998	0.8396	0.5769						
	b1/b2			0.7467	1.4947	0.8464	1.2176	1.8873	1.4657	0.8938	0.6519						
	T1			0.9001	1.1288	2.4572	3.0635	3.6855	4.7979	5.6939	6.2672						
	T2			0.8273	2.5578	1.7102	3.3578	5.2686	7.0316	4.7076	2.9476						
	T2/T1			0.9191	2.2659	0.6960	1.0960	1.4296	1.4655	0.8268	0.4703						
	n	0	0	23	71	37	21	7	8	12	4	0	0	0	0	0	0
0.25 - 0.3	QN1/QN2			1.1201	1.1979	1.0318	0.5835	0.4508	0.3303		0.7355	0.6708					
	b1/b2			1.0704	1.9972	0.8787	0.7976	1.3881	1.4320		1.0110	1.1085					
	T1			0.8168	0.9559	1.7395	2.7095	3.4916	3.9919		5.4806	5.3972					
	T2			1.0010	2.4360	1.5651	1.4184	2.8174	2.0069		4.9538	5.0854					
	T2/T1			1.2256	2.5485	0.8998	0.5235	0.8069	0.5027		0.9039	0.9422					
	n	0	0	12	55	15	37	28	3	0	2	4	0	0	0	0	0
0.3 - 0.35	QN1/QN2			1.2700	1.3335	0.9840	1.2324	0.6130	0.4031			0.6636	0.6371				
	b1/b2			2.1001	2.3541	2.2665	0.6557	1.0522	0.9242			1.1015	1.1647				
	T1			0.5887	0.8312	1.0893	1.7061	2.6123	3.3756			5.4339	5.5168				
	T2			1.7276	2.8139	2.4124	1.3113	1.7221	1.6340			5.1261	5.3904				
	T2/T1			2.9345	3.3856	2.2145	0.7686	0.6592	0.4841			0.9433	0.9771				
	n	0	0	5	18	15	6	12	5	0	0	3	9	0	0	0	0
> 0.35	QN1/QN2			1.4412	1.5994	NA	0.5884	0.5850	1.0149	0.5033							
	b1/b2			2.1288	2.5636	NA	1.0012	2.7765	1.8256	0.9587							
	T1			0.5778	0.5799	NA	2.0984	2.1531	2.3861	3.2834							
	T2			1.8141	2.6626	NA	1.3864	3.7945	4.3926	1.9664							
	T2/T1			3.1397	4.5911	NA	0.6607	1.7623	1.8409	0.5989							
	n	0	0	11	3	0	2	12	1	1	0	0	0	0	0	0	0

Table 33: Track quality parameters after tamping:

> 475 million gt; Q_{N1} 0.54 mm – 0.83 mm.

		QuIt1																
		0 - 0.2	0.2 - 0.4	0.4 - 0.6	0.6 - 0.8	0.8 - 1.0	1.0 - 1.2	1.2 - 1.4	1.4 - 1.6	1.6 - 1.8	1.8 - 2.0	2.0 - 2.2	2.2 - 2.4	2.4 - 2.6	2.6 - 2.8	2.8 - 3.0	> 3.0	
b1	0 - 0,05				1.5569	1.3752	0.8835	1.4535										QN1/QN2
					0.3587	0.3454	0.2715	0.3611										b1/b2
					2.2000	7.2660	7.7180	8.2800										T1
					2.6936	4.1427	1.4841	4.8668										T2
					1.2244	0.5701	0.1923	0.5878										T2/T1
		0	0	0	10	36	36	1	0	0	0	0	0	0	0	0	0	n
	0,05 - 0,1				1.2748	1.0915	1.1493	0.8450	0.8124	0.8244								QN1/QN2
					0.9938	0.6395	0.5820	0.3984	1.1619	1.4164								b1/b2
					2.4691	4.1320	4.1846	7.0792	7.5767	8.4501								T1
					4.3537	3.0612	3.0909	2.1507	6.6112	9.5455								T2
					1.7633	0.7409	0.7387	0.3038	0.8726	1.1296								T2/T1
		0	0	0	53	330	191	49	12	1	0	0	0	0	0	0	0	n
	0,1 - 0,15				1.1848	1.1160	1.0673	1.0935	0.9248	0.7859	0.7063							QN1/QN2
					1.1543	0.9333	0.8386	0.7167	0.8079	0.7637	0.7010							b1/b2
					1.3254	2.5321	3.4387	4.2421	5.4491	7.1719	8.4501							T1
					2.3525	2.8759	3.1846	3.3777	4.0292	4.3668	3.9101							T2
					1.7749	1.1358	0.9261	0.7962	0.7394	0.6089	0.4627							T2/T1
		0	0	0	32	186	310	116	44	18	4	0	0	0	0	0	0	n
	0,15 - 0,2				1.3732	1.0629	0.9671	1.0097	0.7375	1.1447	0.6840	0.6292						QN1/QN2
					1.4391	1.0511	0.9454	0.8886	0.7212	0.6716	0.6126	0.6301						b1/b2
					0.9377	1.8885	2.5537	3.2623	4.5227	5.0558	6.7838	7.0752						T1
					2.6835	2.2020	2.2896	2.9329	2.1707	3.7287	2.9708	3.0541						T2
					2.8617	1.1660	0.8966	0.8990	0.4800	0.7375	0.4379	0.4317						T2/T1
		0	0	0	26	63	168	172	61	31	9	11	0	0	0	0	0	n
	0,2 - 0,25				1.1390	1.4480	1.0656	0.9117	0.9409	0.8389	0.7316	0.7510						QN1/QN2
					2.1510	1.4256	1.1639	1.0514	0.9317	0.9413	1.1359	1.0414						b1/b2
					1.0221	1.1770	2.2364	2.8023	3.1723	3.8937	5.7490	6.3161						T1
					2.8690	2.9357	2.8241	2.6195	2.7444	3.0448	5.4962	5.6782						T2
					2.8070	2.4943	1.2628	0.9348	0.8651	0.7820	0.9560	0.8990						T2/T1
		0	0	0	5	59	63	122	82	18	8	4	0	0	0	0	0	n
	0,25 - 0,3				1.3555	1.2672	1.1238	1.2165	0.7140	0.8052	0.7275	1.0435						QN1/QN2
					1.7447	1.7140	1.5721	1.2760	1.0368	1.0103	0.9102	0.7465						b1/b2
					0.8030	0.9364	1.4015	1.9859	2.9209	3.2719	3.7178	4.1194						T1
					2.3330	2.4374	2.6266	3.1734	1.8480	2.6370	2.3696	3.1617						T2
					2.9053	2.6030	1.8741	1.5980	0.6327	0.8060	0.6374	0.7675						T2/T1
		0	0	0	3	72	41	40	29	15	14	1	0	0	0	0	0	n
	0,3 - 0,35					1.3111	1.0292	0.9353	0.9477	0.6530	0.6479			0.6607				QN1/QN2
						2.1163	1.7991	1.2370	1.7265	1.0909	0.3517			0.4280				b1/b2
						1.0786	1.4806	1.8164	2.0367	2.9275	3.5700			5.6243				T1
						3.2542	2.7623	2.0620	3.2862	1.8095	0.8580			1.8105				T2
						3.0172	1.8657	1.1352	1.6135	0.6181	0.2403			0.3219				T2/T1
		0	0	0	0	19	48	38	15	14	10	0	0	2	0	0	0	n
	0,35-0,4				2.5711	1.4862	1.2709	0.8620	0.7836	0.7133	0.9168							QN1/QN2
					0.8940	0.9699	1.7940	2.5988	1.1011	0.9824	1.0162							b1/b2
					0.5778	0.7172	1.2059	1.3852	2.0013	2.5747	3.2316							T1
					1.3673	1.2471	2.9255	2.8027	1.5926	1.6280	3.1016							T2
					2.3664	1.7388	2.4260	2.0232	0.7958	0.6323	0.9598							T2/T1
		0	0	0	1	3	17	5	3	8	13	0	0	0	0	0	0	n

Table 34: Track quality parameters after tamping:

> 475 million gt; Q_{N1} > 0.83 mm.

		Qult1																
		0 - 0.2	0.2 - 0.4	0.4 - 0.6	0.6 - 0.8	0.8 - 1.0	1.0 - 1.2	1.2 - 1.4	1.4 - 1.6	1.6 - 1.8	1.8 - 2.0	2.0 - 2.2	2.2 - 2.4	2.4 - 2.6	2.6 - 2.8	2.8 - 3.0	> 3.0	
b1	0 - 0,05					1.0572	1.4228	1.5366	0.5508									QN1/QN2
						0.4441	0.4087	0.3321	-0.1123									b1/b2
						2.1079	6.0245	8.2594	0.9471									T1
						1.3968	5.1471	5.3912	3.3787									T2
						0.6626	0.8544	0.6527	3.5674									T2/T1
		0	0	0	0	3	5	7	1	0	0	0	0	0	0	0	0	n
	0,05 - 0,1					1.0861	1.3150	1.1890	1.0996	1.0394	0.9212							QN1/QN2
						0.7732	0.5717	0.4064	0.4807	0.5230	0.3703							b1/b2
						1.6929	2.7189	4.0822	5.0682	8.4519	9.0331							T1
						2.0985	2.9846	2.4157	2.9730	4.6680	2.7899							T2
						1.2395	1.0977	0.5918	0.5866	0.5523	0.3089							T2/T1
		0	0	0	0	5	34	50	35	38	5	0	0	0	0	0	0	n
	0,1 - 0,15						1.0420	1.1266	1.0191	1.0704	0.9626							QN1/QN2
							0.7533	0.6456	0.5409	0.5798	1.3135							b1/b2
							2.3675	2.8863	3.8360	4.1954	4.9384							T1
							2.0134	2.4185	2.1479	2.7742	6.0447							T2
							0.8504	0.8379	0.5599	0.6613	1.2240							T2/T1
		0	0	0	0	0	27	117	144	98	33	0	0	0	0	0	0	n
	0,15 - 0,2						1.4092	1.1246	1.1158	1.0015	0.9153	1.0941	1.4219	1.1764	0.9545			QN1/QN2
							1.4307	0.7785	0.7632	0.7001	0.6838	0.7237	0.5283	0.4533	0.2825			b1/b2
							1.3722	2.1255	2.6670	3.5107	4.2012	4.5307	4.7932	5.6532	7.2321			T1
							4.1270	2.1650	2.5022	2.4643	2.4405	3.6990	3.7931	3.0895	1.9309			T2
							3.0076	1.0186	0.9382	0.7019	0.5809	0.8164	0.7914	0.5465	0.2670			T2/T1
		0	0	0	0	0	8	105	158	87	93	31	14	6	2	0	0	n
	0,2 - 0,25						1.5510	1.6042	1.0442	1.0561	1.0279	1.0404	0.7638	0.8730	1.0692	1.0250		QN1/QN2
							0.8331	0.8228	0.7627	0.9885	0.6100	0.6641	0.7789	0.7230	0.3308	0.5800		b1/b2
							0.7433	1.9757	2.2094	2.7833	2.8847	3.4595	4.5288	5.4587	3.9233	5.7306		T1
							1.7878	2.9489	1.8301	3.0108	1.8535	2.4321	2.3332	3.3926	1.4768	3.4096		T2
							2.4051	1.4925	0.8283	1.0817	0.6425	0.7030	0.5152	0.6215	0.3764	0.5950		T2/T1
		0	0	0	0	0	5	33	93	100	70	23	10	21	22	1	0	n
	0,25 - 0,3						1.7258	1.1909	1.1217	1.0510	0.9792	1.0989	1.0729	1.0142	0.9880	0.9737	0.9522	QN1/QN2
							0.6632	0.4568	0.9007	0.8452	0.8587	0.7216	0.7178	0.6999	0.9934	0.6236	0.6563	b1/b2
							0.7347	1.6860	2.2636	2.4133	2.5787	2.9373	3.0964	3.9324	2.9048	5.7209	5.7731	T1
							1.4059	1.0191	2.3892	2.2020	2.1385	2.4066	2.4793	2.7964	2.7938	3.4864	3.6379	T2
							1.9137	0.6044	1.0555	0.9125	0.8293	0.8193	0.8007	0.7111	0.9618	0.6094	0.6302	T2/T1
		0	0	0	0	0	3	7	33	60	100	57	28	18	16	6	9	n
	0,3 - 0,35						1.4946	0.9174	1.1646	0.9605	1.0552	1.1651	1.1118	1.2412	1.1989	0.8665	0.9105	QN1/QN2
							1.2010	0.3635	1.2273	1.1132	0.9150	0.7726	1.0721	0.8173	1.2081	0.6085	2.7512	b1/b2
							0.7807	1.2879	1.3816	2.0901	2.2771	2.0013	2.5885	3.1071	4.1697	5.7306	5.8682	T1
							2.0362	0.3801	2.2534	2.1818	2.2610	2.0361	3.2609	3.2028	5.9265	3.1874	15.2134	T2
							2.6082	0.2951	1.6310	1.0439	0.9929	1.0174	1.2598	1.0308	1.4213	0.5562	2.5925	T2/T1
		0	0	0	0	0	1	5	21	35	44	34	24	27	3	1	7	n
	0,35-0,4							1.6001	1.2094	1.0451	1.1368	1.0130	1.0839	1.3674	1.1134		0.7580	QN1/QN2
								2.1836	1.2817	1.1284	1.3373	1.1363	0.9678	0.7388	0.7534		2.3016	b1/b2
								0.7124	1.0248	1.7694	2.1006	2.1251	2.3110	2.4747	4.2006		4.8518	T1
								3.9137	1.9719	2.1321	3.3282	2.4649	2.5421	2.6371	3.3636		8.1222	T2
								5.4936	1.9241	1.2049	1.5844	1.1599	1.1000	1.0656	0.8007		1.6741	T2/T1
		0	0	0	0	0	0	3	28	37	26	26	23	28	3	0	1	n

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