Automation of the tamping process

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ABSTRACT

Continuous increase of railway traffic loads forecasted for the next decade will present a major challenge for infrastructure managers. An increased train frequency demands even higher track availability while at the same time shortening the available time frame for maintenance work. As a result, track maintenance has to be planned precisely and performed more effectively. In addition, higher traffic loads will also influence ballast condition by causing increased ballast breakdown in combination with infiltration of fine particles from the surface or subgrade. Together with an increased sleeper wear this will result in a decrease of pore space and permeability of the ballast bed. During this process, individual particles that make up the ballast bed undergo changes in shape, grain roughness and surface structure which are accompanied by a significant decrease in the track ballast internal friction angle, shear strength and overall stability. This process is widely known as ballast fouling and is causing irregular settlements and deviations from the nominal track geometry. The desired track geometry is usually restored using automated tamping machines. They reposition the track and create a resilient support for each sleeper. This is achieved by compacting the ballast matrix directly under the sleeper by dynamic excitation, i.e. oscillating movement of the tamping tines. Changes of the ballast condition and properties require precise adjustment of tamping parameters and machine settings that ultimately influence the resulting track quality. In the first instance the determination and optimization of decisive tamping parameters is necessary to develop a condition-based tamping process thus building a base on which the automation of the tamping process can be built.

1. INTRODUCTION

Track tamping is a core maintenance activity in ballasted track, used to restore the desired track geometry after the deflections have reached a level which no longer ensures safe and cost-efficient train operation. Prior to carrying out the tamping process, lifting, aligning and levelling is conducted. Independent of the tamping technology and tamping machine used, the track is lifted up to the level determined by previous measurements i.e. correction values and simultaneously positioned laterally. In the course of vertical positioning a void is created under the sleeper. During the tamping process, this void is filled with ballast and the ballast is compacted by the tamping tines. The tines execute two different movements: an absolute one toward the sleeper and a relative one represented by the tine oscillation governed by the excitation frequency and amplitude. Both movements transmit the necessary compaction energy to the ballast.

During this complex process, the tamping machine operator can adjust different machine parameters to improve the resulting track quality and the machine's working performance. Parameter selection is, however, based either on experience or on existing standards and/or local specifications. An automation of the tamping process would lead to a reduction of workload for the machine operator and to an improvement of quality of conducted track maintenance.
A system supporting the machine operator in his demanding task is developed in a form of PlasserSmartTamping - The Assistant (Figure 1). This system enables, for the first time, an automation of the tamping process for lines, switches and crossings, at the same time increasing the quality of conducted track tamping and leading to an autonomously operating tamping machine. Laser scanning units are used to record the track and its surroundings and digitize them into a 3D model. The usage of artificial intelligence makes it possible for the system to recognize objects in the track and assign them to the correct category. This enables the machine to autonomously distinguish between rails, sleepers and even obstacles such as cables, located in the sleeper bay. Based on this information the system provides recommended actions for the lifting, leveling and tamping units in "real time" and displays them to the machine operator who can approve or reject recommended actions. As soon as the recommended action is approved, positioning of the lifting, leveling and tamping units is carried out autonomously by the machine [Antony, 2021].

Figure 1: PlasserSmartTamping - The Assistant

Next step in the development of a fully autonomous tamping process is the automation of the tamping unit operation and the selection of tamping parameters in order to provide a homogeneous, durable and stable track bedding. For this purpose, it is necessary to gain a better understanding of the soil mechanical i.e. dynamic component of ballast compaction during tamping. A comprehensive investigation of the tamping process during regular track maintenance in different ballast conditions is conducted in the scope of a research project initiated by Plasser & Theurer and carried out in cooperation with the Institute of Geotechnics at TU Wien in 2016. Main focus of the project was the measurement, recording and analysis of the interaction between the tamping tine and ballast matrix during ballast compaction. Results and conclusions that arose from this research project along with recent developments in the field of tamping process automation are presented and discussed in this paper.

2. GEOTECHNICAL ASPECTS

2.1. Ballast compaction

Continuous compaction and a homogeneous ballast layer constitute a successful track maintenance process and form a stable foundation for a durable track geometry after tamping. Independent of the compaction method, non-cohesive coarse-grained soils (such as track ballast) are compacted primarily by overcoming grain-to-grain friction. This is usually achieved by short-term dynamic effects such as roller or vibratory compaction, track tamping or dynamic track stabilization. Result of a successful compaction is observed in the increase of bulk density and decrease of the void ratio in the affected area.

Determining the rate of success of ballast compaction requires in-situ compaction monitoring. Continuous compaction control (CCC) methods have been developed for several dynamic soil compaction methods (i.e. oscillating rollers). None of these methods can be applied to track ballast compaction, given that the operating principle of track maintenance machines dictates that the optimum final compaction has to be achieved after a single machine employment – a task that can only be achieved if the process is condition-based meaning the tamping parameters such as tamping time, pressure and number of insertions can be adapted to the ballast bed condition encountered in-situ [Barbir and Antony, 2022]. An additional important aspect to consider is that the compacted ballast is located lengthwise under the sleeper which significantly aggravates the employment of any existing compaction control mechanisms [Barbir, 2022].

Depending on the initial bulk density of the ballast bed, the compaction energy introduced (e.g. during track tamping) causes the individual ballast grains to be rearranged, resulting in a state of higher bearing density. It should be noted that, in the context of ballast compaction, the objective is not to achieve the densest bedding, but to achieve the optimum compaction or bedding density without causing wear of the ballast matrix – changes to the grain size distribution, surface roughness, grain shape etc. Definition of optimum compaction is dependent on the ballast condition.

2.2. Ballast condition and condition determination

From an economic point of view, the most desirable method of preventive maintenance is condition-based, meaning that decisive tamping parameters should be adjusted to the encountered track condition, thereby extending the track service life. In order to be able to do so, a reliable method of ballast condition determination has to be used. Several ballast bed condition assessment methods and factors such as fouling index, percentage of fouling, percentage void contamination or void contaminant index are known and used throughout the world (in detail in [Barbir, 2022]). All of them, however, require in-situ sampling followed by laboratory tests determining either the grain size distribution, void ratio, unit weight, dry mass or similar characteristics of a representative ballast sample or the fouling material contained in the sample. The sampling itself reduces track availability and creates a necessity for additional track closure, making the determination of ballast condition a time-consuming and challenging task [Barbir and Antony, 2022].

Another shortcoming of the existing ballast bed condition determination methods is that they only provide a selective overview of the ballast bed condition, even if they do give detailed information about the ballast matrix. An additional possibility to determine the ballast bed condition in-situ is the utilization of the Ground-penetrating radar (GPR). This non-destructive method of surveying the superstructure at comparatively high speeds is increasingly used to monitor track condition. GPR distinguishes between different ballast conditions primarily based on the existence of moisture trapped in fouled sections. One of the major advantages of the GPR is that it provides information about the ballast bed condition continuously rather than at selected sampling points. However, a great deal of effort and experience is subsequently required to interpret the data recorded by the GPR correctly [Barbir et al., 2021].

2.3. Ballast bed shear strength in different ballast conditions

Ballast shearing behavior is greatly influenced by the changes in the grain size distribution that occurs as a consequence of ballast fouling by different materials. One of the most broadly used parameters to validate soil compaction and describe mechanical properties of compacted soils in different conditions is the dynamic shear modulus G_d, representing the ratio of shear stress to shear strain under dynamic loading conditions. The dynamic shear modulus can be determined in-situ in dependence on the bulk density ρ and by measuring the shear wave velocity c_s using the following equation:

$$G_d = c_s^{\ 2} \cdot \rho \qquad \text{(Eq. 1)}$$

As can be seen in Figure 2, dependent on the fouling of the material, the dynamic shear modulus decreases as the fouling progresses. In this case, ballast fouling is determined by the percentage of fouling, determined as the ratio of the dry weight of material passing a 9.5 mm sieve to the dry weight of the total sample [Seling and Waters, 1994]. Figure 2 shows that the initial increase of the percentage of fouling increases the dynamic shear modulus which is similar to an increase of density due to initial fouling [Indraratna et al., 2011]. Shear wave velocity would show analogous behavior. G_d of clean ballast increases up to the optimal fouling point (OFP) defined with G_{max}. Dynamic shear modulus decreases as the fouling progresses beyond the optimal fouling point, but it is still higher than in new ballast conditions meaning that the track is sufficiently resistant. The fouling process continues until the critical fouling point (CFP, defined dependent on local conditions) is reached. At the CFP, the modulus is equal to the one of new ballast and decreases further beyond this point, making the track drainage conditions unsuitable [Barbir, 2022].

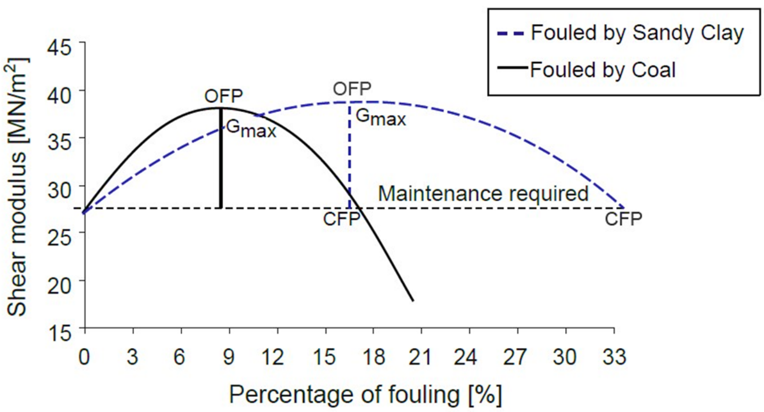

Figure 2: Variation of shear modulus (modified from [Indraranta et al., 2011])

3. BASIC RESEARCH

Significantly more precise and reliable information on the ballast bed condition in comparison to all the methods listed in Chapter 2 could be achieved if the condition of the ballast bed is determined on-the-spot, i.e. directly during track tamping by the tamping machine itself. This approach builds the basis for further automation of the tamping process by developing a *Smart Tamping Sensor*. In addition, an on-the-spot determination of the ballast condition would make adapting decisive tamping parameters to the ballast condition possible, thereby increasing the efficiency of maintenance work and optimizing ballast life cycle.

In order to make the on-the-spot condition determination possible, a specially developed measurement system was implemented directly to the Plasser & Theurer tamping units of a four-sleeper track tamping machine *Dynamic Tamping Express 09-4X E³* as well as to a single sleeper track and turnout tamping machine *Unimat 09-4x4/4s E³* (Figure 3a).

The sensor set-up consists of strain gauges (Figure 3b; red) that are applied and used to measure the penetration resistance and reaction forces at the tamping tine plate. Accelerometers (Figure 3b; blue) placed on the upper point of the tamping arm allowed for a precise calculation of the tine oscillation amplitude in a local coordinate system. In conjunction with pressure sensors (Figure 3b; yellow) and elongation measurements at the hydraulic cylinders (Figure 3b; green) the tamping process could be fully documented and subdivided into the respective operating phases – (1) ballast penetration, (2) squeezing movement and (3) tamping unit lifting and/or relocation to the next sleeper (Figure 4). [Barbir et al., 2021].

a) b)

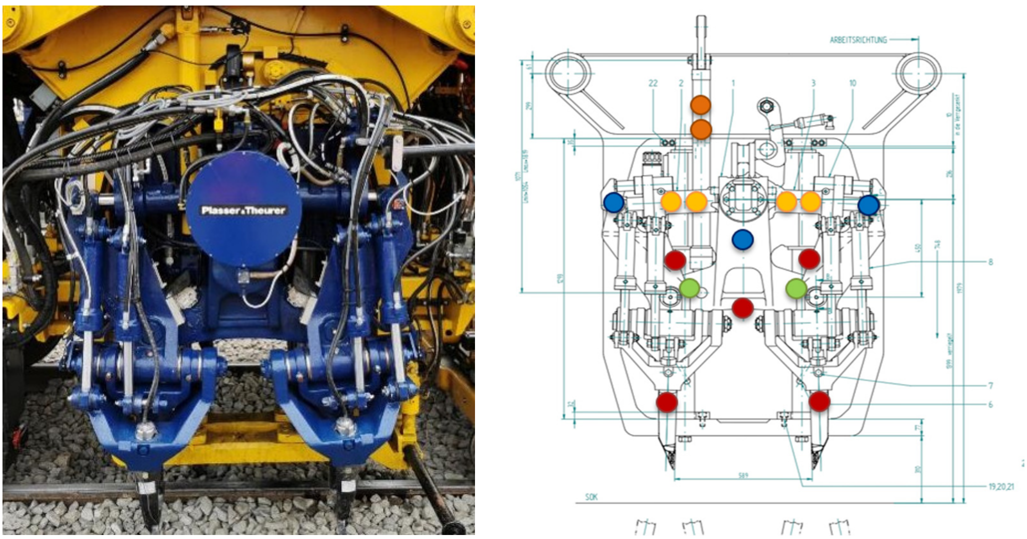

Figure 3: (a) Tamping unit of the universal tamping machine *Unimat 09-4x4/4s E³* (b) Position of the installed sensors

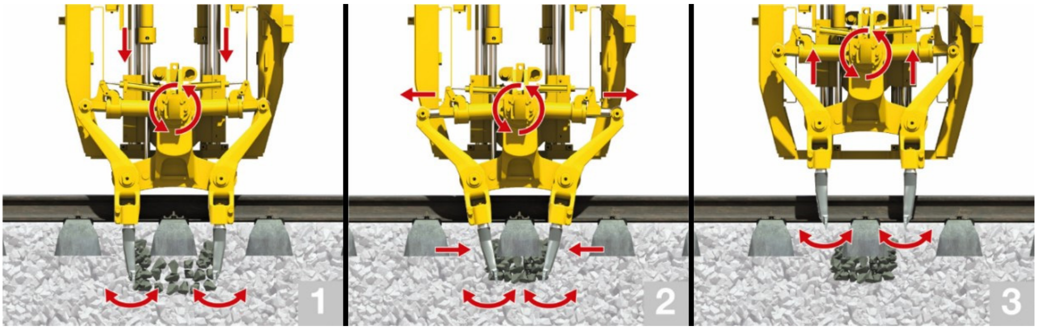

Figure 4: Tamping process subdivision: (1) ballast penetration, (2) squeezing movement, (3) lifting followed by the relocation of the tamping unit

The described measurement system is used primarily to record the interaction between the tamping tine and the ballast matrix during ballast compaction. These two components are observed on a vibration cycle scale, and a new method of measuring and interpretation of their force-deformation relationship in form of a load-displacement diagram (Figure 5) is developed. Every cycle can be further subdivided into the loading (tamping tine movement in the squeezing direction) unloading (tamping tine movement opposite of the squeezing direction) and withdraw (contactless) phases. This method of dynamic measurement analysis [Plasser Theurer, 2017] allows for an insight into the following tamping characteristics, essential for a successful data evaluation:

- oscillation amplitude i.e. displacement
- maximal reaction force per cycle F_{max}
- ballast matrix response during loading and unloading
- energy transferred into the ballast (red area underneath the load-displacement curve)
- points of tamping tine-ballast begin and loss of contact

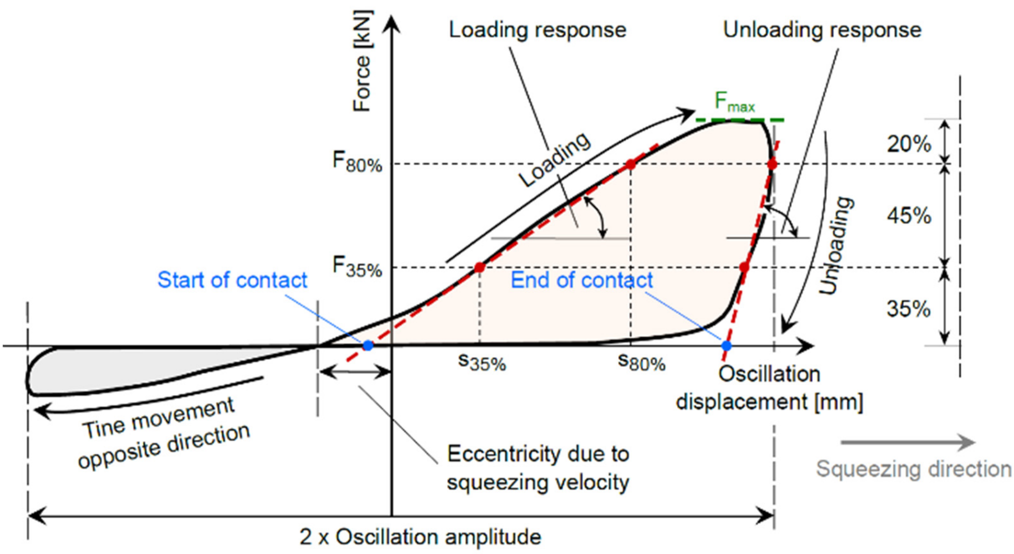

Figure 5: Simplified load-displacement curve [Barbir, 2022]

It was, for the first time, proven by measurements that a periodic loss with a subsequent gain of contact between the tamping tine and the ballast matrix occurs. In contrast to static compaction, periodic contact loss and contact gain allow the ballast grains in the contactless phase to rearrange, resulting in a denser bedding achieved by lower acting tamping forces.
Relevant differences between ballast conditions are found for the following four tamping characteristics:

1. Maximal reaction force per cycle
2. Energy per cycle
3. Ballast matrix response during loading
4. Ballast matrix response during unloading (shape of the load-displacement diagram)

Significantly higher tamping force, energy and loading response are measured in fouled ballast conditions. In addition, the shape of the diagram in the unloading phase clearly indicates the changes of the ballast conditions, influenced by an increase of proportion of fines with the progress of ballast fouling, which increases ballast resistance to further compaction.
Based on the evaluation of selected measurement data, decisive tamping characteristics are defined for the following ballast bed conditions:

- clean ballast, tamping conducted following track renewal,
- fouled ballast with high content of fines, tamping in the scope of during track maintenance.

4. SEMI-ANALYTICAL MODEL OF THE TAMPING UNIT - BALLAST MATRIX INTERACTION

In order to investigate the influence of the ballast bed condition on the quality and durability of the conducted track tamping, a semi-analytical mechanical model of the tamping tine - ballast matrix interaction during the squeezing movement is developed. The model depicts both relative, governed by the dynamic excitation, and absolute motion of the tamping tine governed by the squeezing velocity. It consists of two fundamental parts: tamping unit and ballast matrix model [Barbir, 2022].
The tamping unit is modelled as a simple system of rods with a dynamic excitation overlapped by a hydraulic cylinder movement modelled with a variable rod length. Tamping unit geometry of the *Dynamic Tamping Express 09-4X E³* was used for the mechanical model and the exact positioning of the tamping tine (x_{tine}, Figure 6) is obtained and taken as an input for the ballast matrix model.
Soil i.e. ballast matrix model reaction to the tamping tine motion is modelled by a Kelvin-Voigt model consisting of a purely elastic spring with a stiffness k_e and a purely viscous damper with a coefficient c_e connected in parallel based on the cone model theory according to [Wolf, 1994]. The model described adapts the theory of the Zener or standard linear solid model in the Kelvin representation, used to describe both, the creep and stress relaxation behavior of viscoelastic materials [Barbir, 2022]. Using the cone model allows for a description of the ballast matrix using its soil mechanical properties – shear modulus, density and Poisson's ratio. The residual (plastic) deformation of the ballast matrix is simulated by a spring with a stiffness k_p that is compressed during loading and remains "locked" during the unloading phase. In case of loss of contact, a gap appears between the tamping tine and the ballast matrix. Ballast grains strive to fill this void, causing the tine to reinitiate contact with the ballast matrix sooner in the following cycle. The influence of the ballast grain movement during the loss of contact is calculated as the “gap-closing acceleration” a_{gc} [Barbir et al., 2019]. Force F (Figure 6) is calculated from the soil model and used as an input for the calculation of the exact tine position in the next cycle.

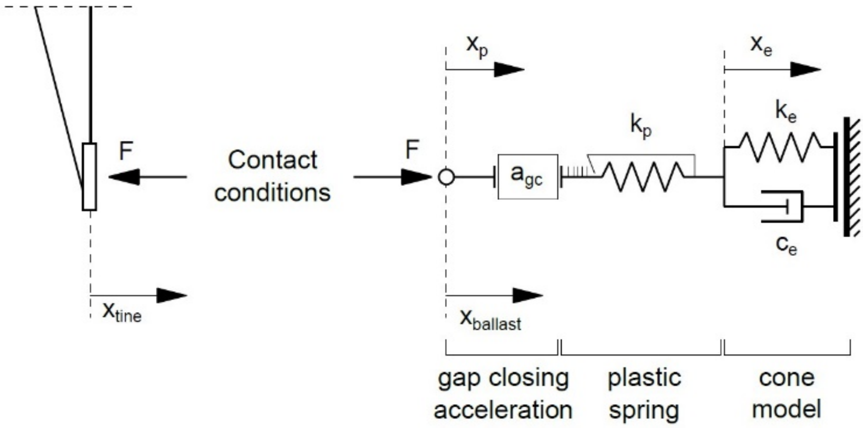

Figure 6: Ballast matrix model with its three components

Based on the in-situ measurements, "model-updating" was conducted – ballast matrix parameters were modified in order to simulate ballast behavior observed during the in-situ measurements. Load-displacement diagrams as well as tamping characteristics described in the previous chapter were successfully reproduced by the model. In order to conduct a model verification, an effort was made to simulate different ballast fouling stages by using the semi-analytical approach. One of the most important steps forwards in the model development was recognizing the elastic spring constant k_e as a parameter that can be varied to achieve the desired effect i.e. simulate the process of ballast fouling (Figure 7). Elastic spring constant for modeling fouled ballast condition is calculated using the cone model whereas a significant reduction of the elastic spring constant (by a factor of 10^3) was necessary to simulate tamping in clean ballast condition. A high level of correlation between the two approaches can be observed (Figure 7), confirming the reliability of the developed model.

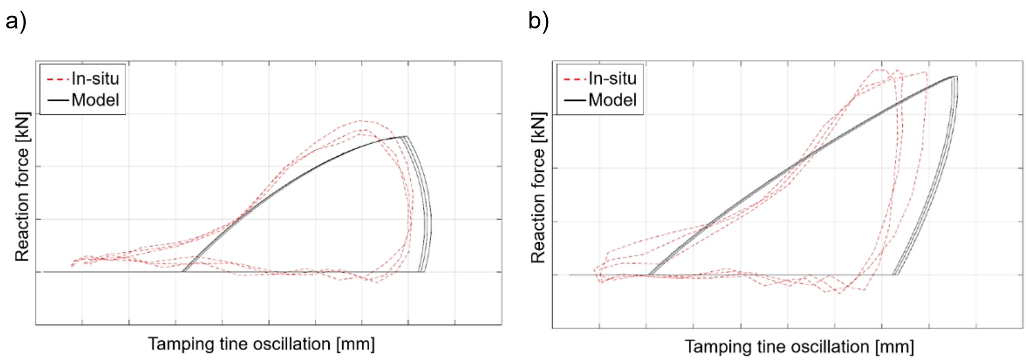

Figure 7: Load-displacement curves of the two selected in-situ measurements conducted by the *Dynamic Tamping Express 09-4X E³* compared to the mechanical model: (a) clean, (b) fouled ballast

5. CONCLUSIONS AND OUTLOOK

Fundamental research forms the basis for the development of new products. Tamping units have been empirically optimized and further developed throughout the course of their existence. At a certain point, however, empirical methods reach their limit, from which point on new impetus must be provided by scientific investigation. For this reason, tamping machines have been and are increasingly being equipped with additional measurement systems in order to enable the recording and understanding of the tamping process more precisely. Findings from these investigations and experiments are the foundation for the development of new technologies in the field of smart i.e. autonomous track tamping as well as for transforming and upgrading the tamping unit from a track maintenance tool into a measuring device.

Recording machine parameter settings as well as the data documented during track tamping and tamping unit positioning enables a complete transparency of the tamping process. From the infrastructure manager point of view this system enables a new type of verification documentation. All tamping process aspects and parameters that are considered quality-relevant are recorded in the tamping protocol (Figure 8). The system has a modular structure – basic version comprises the control of lifting and leveling units and can be extended to control the tamping unit [Antony, 2021].

In an attempt to minimize the variation of different working methods, regulations and ballast types, the basic research was conducted on railways in Austria. Following the basic research described in this paper, tamping machines in Europe (2018), Japan (2021) and the US (2022) have been equipped with similar measurement systems that enable detailed monitoring and analysis of the entire tamping process down to each single tamping tine oscillation. This will further sharpen the ballast condition definition and condition determination possibilities.

In order to optimize the evaluation algorithms and increase the reliability of the system, the data recorded by the measurement system described in Chapter 3 is compared to existing infrastructure data. For this purpose, a corresponding cooperation project has been set up between ÖBB, SBB, TU Graz and Plasser & Theurer. This cooperation will significantly advance the in-situ analysis of ballast condition in the coming years.

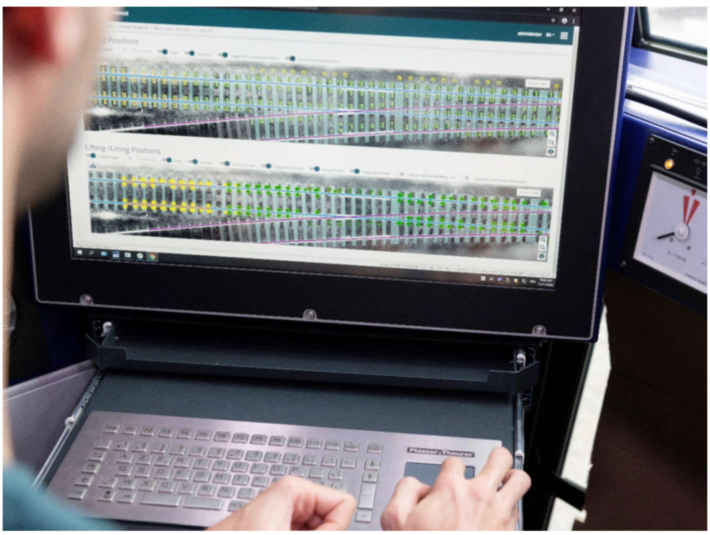

Figure 8: PlasserSmartTamping protocol

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