JOURNAL OF PROCEEDINGS

THE PERMANENT WAY INSTITUTION &

THE UNION OF EUROPEAN RAILWAY ENGINEER ASSOCIATIONS

16TH OCTOBER 2018 - MANCHESTER CONFERENCE CENTRE UK

Elastic elements in track influencing total track costs and reducing vibrations

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INTRODUCTION

Under Sleeper Pads (USP) are associated with having a positive impact on track behaviour of ballasted track and reducing vibration.

IMPACT OF UNDER SLEEPER PADS ON TRACK SUSTAINABILITY

Starting with the impact on track behaviour one question should be addressed: Why do concrete sleepers need further development? The implementation of concrete sleepers has given track much better stability in increasing the lateral track resistance and thus lowering the maintenance requirements. The one world record run in 1955 with 331 km/h destroyed the wooden sleeper track. There were two main reasons: little lateral track resistance due to the light superstructure and the manual maintenance not allowing continuity of track quality, neither in track laying nor within track maintenance.

These problems were solved impressively long before Under Sleeper Pads were in use by implementing mechanised track renewal and maintenance and heavy superstructure with 60 kg rails and concrete sleepers. After the world record run in 2007 at 574.8 km/h, the track was opened for operation without any maintenance action necessary. Furthermore, concrete sleepers are cheaper than wooden ones and show a longer service life. Thus, not only loads and speeds could be increased but also the life cycle cost of superstructure was reduced by using concrete sleepers. However, concrete sleepers still show one main disadvantage compared to wooden ones: the contact area between the sleeper and ballast is very small. Tests using black paper below the sleepers allowed the contact area between ballast and sleeper after tamping to be identified. The used ballast in Austria has a maximum size of 63 mm. The use of a dynamic track stabiliser (DGS) showed significant differences in the results as presented in **figure 1**.

On the one hand the results show the effectiveness of track stabilising; on the other hand, high ballast degradation when using concrete sleepers is evident. The hard-to-hard situation in this contact area causes only a few, highly overloaded contact points forming the starting points for a limited number of “force-paths” through the ballast structure rather than allowing the entire ballast structure to act as a sleeper-support. Edges and corners are quickly cracked off, leading to these unpredictable initial settlements. As the number of “force-paths” varies under neighbouring sleepers, the sleepers settle differently, causing initial errors; equal to a reduced initial quality and increasing the rate of deterioration. To summarise: the bigger the contact area, the smaller the initial settlement is and thus the differences between these settlements; the higher the contact area between sleeper and ballast the higher the initial track quality.

These results have been very promising from a technical point of view. However, installation of Under Sleeper Pads can cause additional investment costs. To analyse the efficiency of this additional investment from an economic point of view, the technical effects (track quality behaviour) must be analysed over the entire service life of track (life cycle costing) as just a life cycle approach allows the evaluation of the economic efficiency of various track types. In order to do this the behaviour of track must be analysed, as understanding of track behaviour is the precondition of forecasting it and thus evaluating life cycle behaviour and life cycle cost of track. Within an extensive research program at Graz University of Technology in cooperation with the Austrian Federal Railways Infrastructure, track behaviour over time was analysed.

All the following results described are based on the extensive data of the Austrian Federal Railways. Testing Under Sleeper Pads had already started in the late 1990s. Implementation of USP in ballasted track in Austria began roughly 20 years ago.

The tests and the analyses of the change of track behaviour led to the general implementation of under sleeper pads for concrete sleepers at Austrian Federal Railways. The respective regulations are in power since 2007. **Figure 2** depicts the implementation of Under Sleeper Pads on the network of the Austrian Federal Railways over time. There are still some wooden sleepers installed e.g. on sharp curves, sidings and branch lines. Concrete sleepers without USP are built in mainly in case of single sleeper exchange and short sections of track renewal. The reason is to avoid too many places where superstructure with and without USP meet, as these two types of superstructure show significantly different behaviour.

Track behaviour is evaluated when analysing time sequences of track recording data. In the case of USPs, up to 2017, 60,000 sections with USP have been compared with respective sections without USP. It can be shown that track deterioration is cut in half with regards to levelling-lining-tamping. This is caused by an increase of the contact area between the sleeper and the ballast bed. Measuring in track and lab shows up to three times higher contact areas using USP. This reduces the stresses in the ballast bed. Furthermore, it also has a very positive impact on track service life as in case of good subsoil worn out ballast is limiting track service life. In Austria, there are also hundreds of switches equipped with USP. Based on the analyses of track behaviour a life cycle cost evaluation was conducted taking the above described effects on track behaviour into account.

TRACK QUALITY BEHAVIOUR

When describing track quality behaviour, various conditions such as transport volume, type of superstructure, quality and status of all components, alignment (radii), ballast quality, quality of sub-layer as well as sub-soil, the functioning of the dewatering system, position of stations, bridges and turnouts must be taken into account. Therefore, a data-warehouse was set up covering track recording car data (initial status, present status, and quality figures), type and age of superstructure and sub-structure and transport load. The research was based on this data for the main railway network of Austrian Federal Railways covering time sequences over the past 17 years (**figure 3**).

This structure allows the comparison of different types of superstructure for a big number of sections facing the same boundary conditions. The comparisons can be done every 5m for a data set of 4,000 km in total and thus provides a big number of comparable sections. This allows the identification of the effects of initial quality as well as calculating the specific deterioration rate for a given set of boundary conditions and different types of superstructure.

The results are very promising as the ballast is identified to be the element limiting the economic service life of track.

This underlines the expectations of Under Sleeper Pads as stresses in the ballast bed are reduced due to the increasing contact area between sleeper and ballast (**figure 3a**).

LIFE CYCLE COSTING

Life Cycle Costing (LCC) is a process whereby costs of various project alternatives are considered for building and maintaining an asset. These alternatives must all provide the same level of service and benefits to be effectively compared using LCC. Total costs under the LCC methodology are initial design respectively the costs of re-investment and construction, ongoing maintenance costs and scrap value or disposal cost for the previous asset. All these costs are gathered for each alternative. Then the user discounts the costs back to present day Euros and summarises them. Engineering departments typically have problems with convincing management to accept a higher initial cost in order to save on maintenance or to allow longer service lives. The LCC analysis plainly demonstrates the total cost which may aid in management discussions.

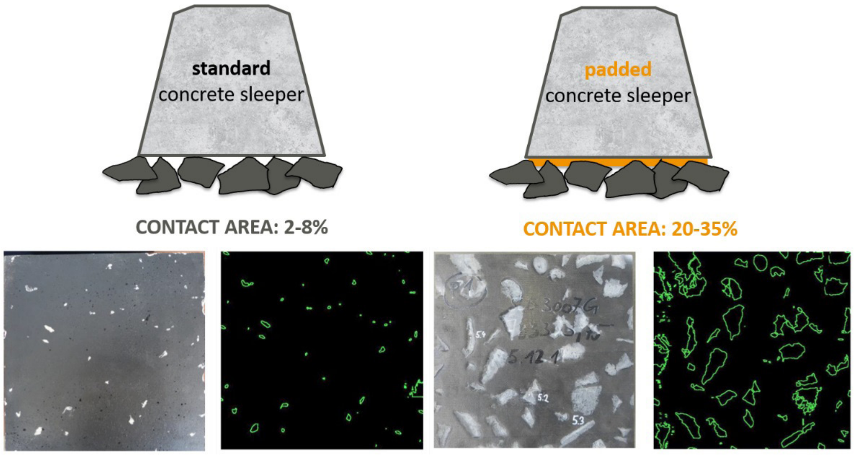


Figure 1: Contact area sleeper – ballast

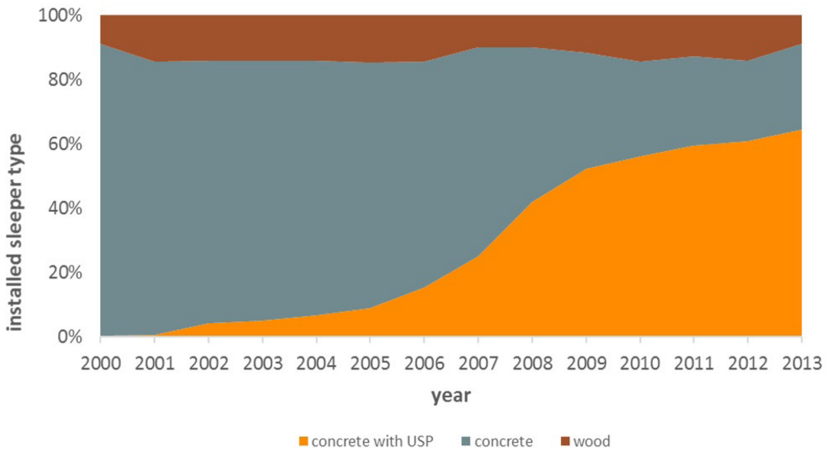


Figure 2: Implementation of under sleeper pads at Austrian Federal Railways

However, there are other decision factors that need to be addressed: risk, future availability, best maintenance practices and environmental concerns, just to mention a few that may be unique to a certain project. Some of these factors may be addressed by increasing future costs. As LCC addresses only those decision factors that can be stated monetarily, costs of operational hindrances become important in describing costs of reduced availability. Application of LCC techniques provides management with an improved awareness of the factors that drive cost. Thorough analysis of the construction and the ongoing maintenance are outlined in detail so as to make omissions more obvious to the LCC creators. It is important that the cost drivers are identified as completely as possible so that the ultimate decision makers can make the most informed decision.

Two attributes of permanent way make life cycle costing especially useful in the field of railway infrastructure: an extremely long service life and a strong relation between initial quality, maintenance demands and service life. Investment determines the initial track quality, while maintenance affects future track quality and service life. Both investment and maintenance strategies must be considered together, as focusing on investment strategies or isolated maintenance regimes will lead to sub-optimal decisions.

It is difficult to predict the total life cycle cost of long-lasting assets because of the likelihood that there will be unexpected changes related to component costs and maintenance productivity. Moreover, LCC analyses usually focus on the factors and cost categories that are most affected by the alternatives that are being investigated. Therefore, the LCC values that result from a study are not necessarily complete or accurate or suitable for decision-making.

It is much better to compare different options by looking at the differences in life cycle costs. These differences can be directly tied to the features that are expected to differ among the various options. The best option will be the one that is expected to have the greatest reduction in LCC from the base case. Note that the LCC is expressed as an annuity (i.e. as an equivalent annual cost over the life of a project). Sensitivity analyses are generally conducted as part of life cycle cost evaluations to attach critical values for sensitive input data. The discounting rates depend on the service life of the project calculated. Discounting rates of a maximum of 5% net are generally in use for service lives of 30 and more years.

One of the most important figures within LCC is the service life. Unfortunately the service life is not a given fixed value, but is influenced significantly by the initial quality and the maintenance executed.

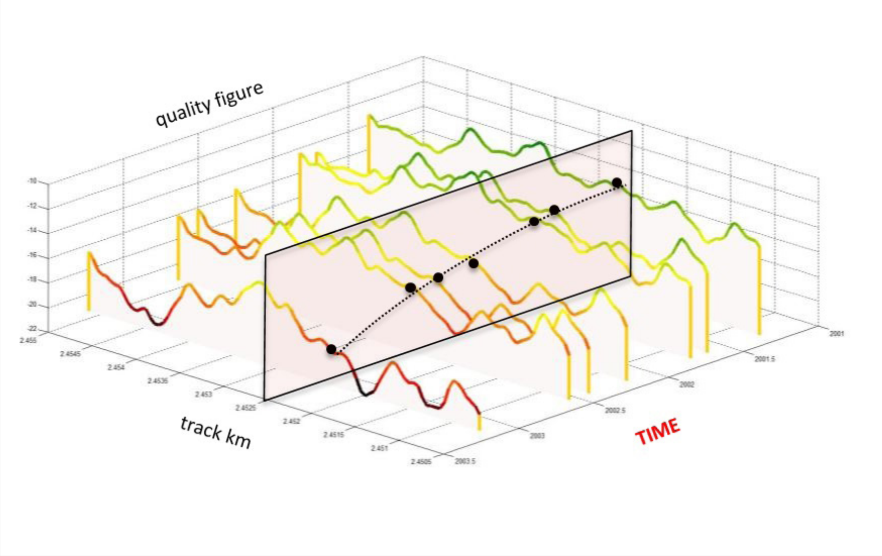


Figure 3: Analyses of track behaviour over time

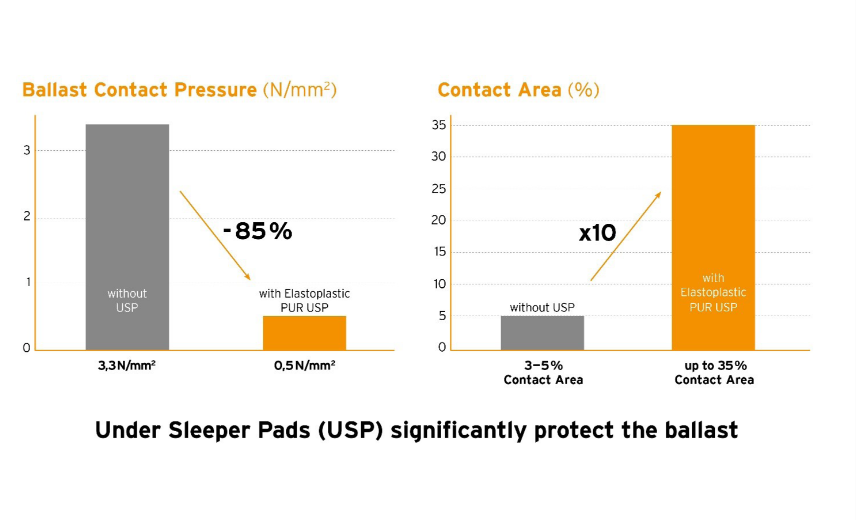


Figure 3a: Reduction of ballast contact pressure with USP

Figure 4: Internal rate of return for the additional investment into under sleeper pads

Furthermore, it must be differentiated between the technical and the economic service life, as the technical service life can be increased by expensive maintenance actions as single sleeper exchange or by limiting the operation in speed and/or axle load. However, this must not be the target as it leads to high costs and poor performance. The economic service life is the time span resulting in the annual cost. The economic service life is reached as soon as the additional maintenance necessary to prolong service life is more costly than the reduction of depreciation due to the prolonged service life.

It can be mathematically proven that the ratio of the maintenance intervals is indirectly proportional to the that of deterioration rates. In other words, this means that a halved deterioration rate leads to a doubled interval for tamping actions and points out the importance of the rate of deterioration. Furthermore, research has shown, that increasing maintenance cycles due to high quality leads to a remarkable increase of service life. However, if the maintenance level is reduced leading to poor quality, service life will be shortened. These effects depict the overwhelming importance of track quality, namely the initial quality and the deterioration rate, for service life, maintenance demand and thus the life cycle cost of track.

RESULTS COMPARING STANDARD TRACK AND TRACK WITH UNDER SLEEPER PADS

As the deterioration rate differs widely due to the various boundary conditions, comparing track with and without USP requires comparing these two types of ballasted track facing the same boundary conditions. Elastic footings for concrete sleepers have been under investigation for quite a long time throughout Europe. It is obvious from the test results that track deterioration is reduced dramatically due to the use of Under Sleeper Pads (**figure 3**). The general results showed that:

- the initial quality is increased by 18 per cent
- the tamping cycle can be prolonged without loss of quality in a range from 2.00 to 3.00
- the service life should increase by more than one third

The initial quality of USP tracks is better than that of conventional tracks as the initial settlements of track are reduced and with reducing these settlements to their absolute differences, the initial errors are reduced automatically.

This data forms the input data for calculating the economic efficiency of USP. The calculation is based on Austrian cost figures. The additional cost of USP is 30% of sleeper costs including fastenings. In order not to associate the results to a specific cost, level numerous sensitivity analyses have been

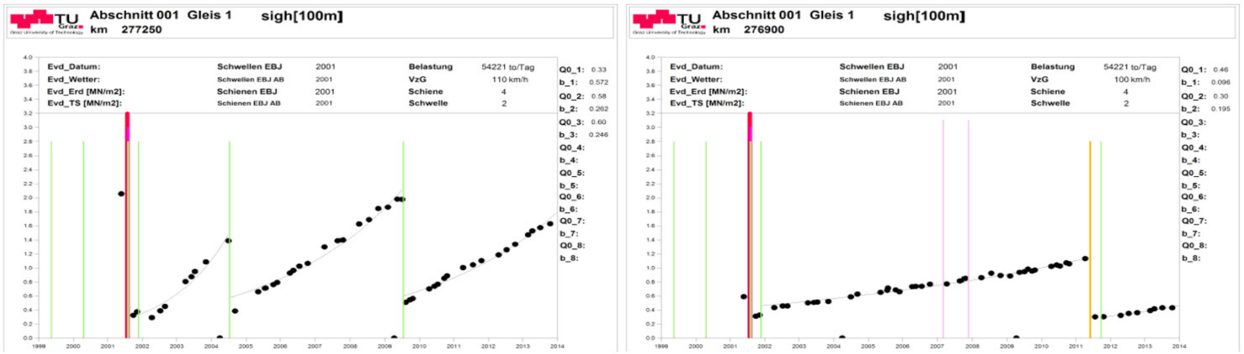


Figure 5: Development of track quality

carried out in varying specific cost data. The economic evaluation shows that this reduction leads to enormous savings in terms of total LCC justifying the relatively low additional investment cost. However, savings are higher, the higher traffic loads are (**figure 4**). Therefore, the Austrian Federal Railways (ÖBB) started to implement USP equipped concrete sleepers as a standard solution on highly loaded tracks (more than 30,000 daily gross tons per track), sharp curves (less than 600 m), high speed (more than 160 km/h), and turnouts, first.

As further results for other boundary conditions (e.g. curved track) are also published in the UIC leaflet, in the following additional results regarding initial quality, quality after tamping and expected service life will be discussed, based already on more than 60,000 cross sections compared. **Figure 5** shows typical track quality behaviour for a section of 54,000 gross tons per day and track, on the left side conventional ballasted track with rails 60E1 on conventional concrete sleepers, on the right hand side the same superstructure but with USP. The vertical red line shows the time of renewal, the green line a tamping action.

However, this is just a specific result. Therefore, in **figure 6** the quality after tamping and the deterioration rate is given for all checked sections. The quality deterioration rate is reduced from 0.14 to 0.07 as was expected by the theoretical calculations. The quality after tamping is reduced from 0.5 mm standard deviation to 0.3 mm. As the analyses are based on Austrian data, all tamping actions were stabilised.

These results underline the technical and consequently the economic efficiency of Under Sleeper Pads. **Figure 7** summarises the characteristics of wooden sleepers, concrete sleepers and concrete sleepers with Under Sleeper Pads. The durability of the concrete sleepers stays the same, the lateral track resistance is increased as the ballast stones can press into the pads. Durability of track increases as the critical element of the ballasted track, the ballast, faces lower loads.

In Austria, concrete sleepers are the cheapest solution for the available investment, concrete sleepers with Under Sleeper Pads are the same price as wooden sleepers. However, cost of track renewal increases by 5%, service life is prolonged by more than one third and maintenance can be reduced down to 50% (average values for track on good sub-soil with proper dewatering systems). These facts result in an average reduction of total life cycle cost by one third.

VIBRATION ISOLATION WITH UNDER SLEEPER PADS

While USPs are excellent for reducing maintenance costs, which has been already outlined in detail, they are also a cost efficient and effective measure for reducing vibrations and secondary air-borne noise next to ballasted track superstructure (refer to **figure 8**). Highly elastic pads offer a simple method for reducing vibrations on railway lines that is cost effective in comparison with Under Ballast Mats (UBM). In addition, they exhibit all the positive properties of elastoplastic USP, such as an increase of contact area and thus reduction of LCC.

One advantage of USP over UBM is, that retrofitting can be executed a lot easier with USP, as sleepers can be exchanged one by one. Installation of UBM in an already existing track would be a lot more complex and costly. The vibration attenuation performance of UBM is of course higher, due to the full-surface decoupling, the bigger mass and the lower stiffness of the elastic layer. The decision between USP and UBM is a trade-off between total cost (product plus installation) and attenuation performance and has to be taken on the basis of project specific boundary conditions.

Elastic sleeper pads with vibration isolating characteristics are a very effective measure for reducing secondary air-borne noise. Since the vibration and sound emissions of the railway track are also significantly dependant on the quality of the superstructure, the more even the superstructure is, the lower the emissions are. In addition to this effect, the physical principle of vibration isolation plays a big part in the reduction of emissions. The performance of a vibration isolation solution is dependent on factors like overall mass, stiffness and system damping. By means of inserting an elastic element such as USP, an oscillating system is created.

In the best case the frequency of the system is way below the spectrum of exciting frequencies that should be isolated. This is based on the principle of the one mass one spring single degree of freedom oscillator. The dynamic stiffness of the USP used must be tailored to the specific installation situation and the constraints of the project. Only if the technical solution is carefully engineered will the USPs be able to exploit their full vibration isolation performance.

VALIDATION OF VIBRATION ISOLATION WITH USP

The vibration attenuation performance of elastic elements in the installed state is generally quantified by the insertion loss. The insertion loss describes the relative performance of an attenuation solution compared to a reference situation, answering the question of how the one-third octave bands of the structure borne noise change after installing USP. To enable this comparison, a ceteris paribus principle should be followed: the train, the speed, the roughness of the rail and other parameters shall ideally be the exact same or at least very similar to make a valid insertion loss calculation possible.

Depending on the maximum permissible rail deflection, padded sleepers achieve insertion losses in the order of 10 dB(v) to 15 dB(v) (at 63 Hz). 10 dB(v) of reduction are equal to an

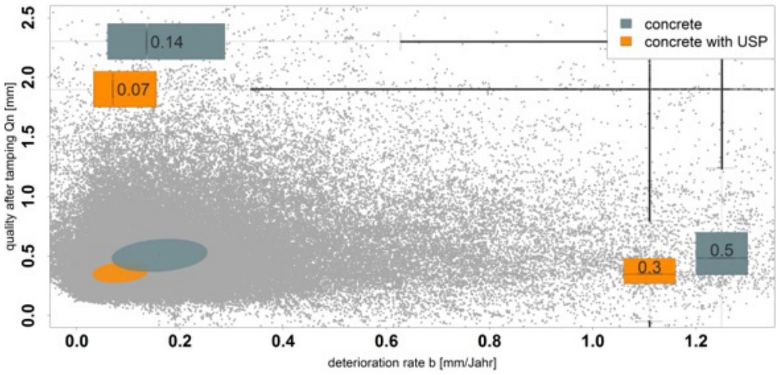
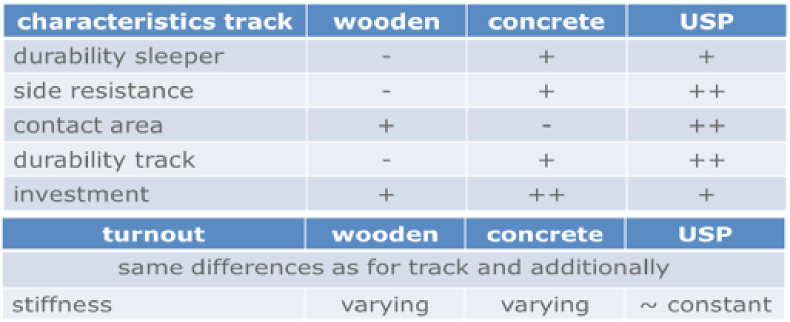


Figure 6: Impact on quality and track deterioration by installing USP



characteristics track	wooden	concrete	USP
durability sleeper	-	+	+
side resistance	-	+	++
contact area	+	-	++
durability track	-	+	++
investment	+	++	+
turnout	**wooden**	**concrete**	**USP**
same differences as for track and additionally			
stiffness	varying	varying	~ constant

Figure 7: Characteristics of ballasted track with different types of sleepers

isolation performance (reduction) of 69%! Secondary air borne noise arises due to the sound emission of a structure that is stimulated to vibrate, for example by a passing train. This applies in particular to metal structures, such as steel bridges and viaducts.

Measurements in track comply with the theoretical calculations based on the impedance model. Most recently a railway track in Poland was assessed by experts from Wroclaw University of Technology and the R&D department of Getzner Werkstoffe. The dominant one-third octave band of passing trains can generally be found at 63 Hz. The use of Sylomer® USPs resulted in an insertion loss of 11.6db(v), which is equal to an average vibration reduction of 74 per cent. Vibrations are reduced at frequencies above 31.5 Hz compared to the track without any elastic elements. In the range of the natural frequency only a very small resonance amplification could be observed. These investigations, especially at the relevant frequency range of 63 Hz, demonstrate the fundamental suitability of USP in reducing vibrations and secondary airborne noise.

PROJECT EXAMPLE: LONDON UNDERGROUND

The track of the London Underground District Line was completely renewed between Paddington and High Street Kensington stations. Around 173 million passengers use this line every year. Starting in July 2011, this very busy section of track, which is also part of the Circle Line, was upgraded with new ballast, rails and brand new sleepers with pads supplied by Getzner Werkstoffe. The sleeper pads protect the track superstructure and reduce the level of vibrations caused by the underground trains.

They also have a beneficial effect on the numerous dwellings alongside the track, as the decrease in vibrations noticeably improves the residents' quality of life.

Providing elastic bearings for this stretch of the District Line was the first major sleeper pad project for London Underground: the vibration protection requirements called for the use of full-surface Sylodyn® sleeper pads, which are ideal for effectively minimising vibrations. Deliveries were made both to the CEMEX sleeper works and directly to London Underground. This renovated section of the District Line runs through very narrow tunnels, meaning that there is little or no gap between the sleepers and the drainage channels adjacent to the tunnel wall. A particular challenge in this case was preventing an increase in the level of sound transmission through the tunnel walls. The elastic Sylodyn® bearings were for the first time placed not only on the bottom of the sleepers, but also on the ends (refer to **figure 10**), thus reducing the transmission of noise and vibrations through the tunnel wall.

Around 7,000 pads for concrete sleepers and roughly 1,000 pads for timber sleepers were used on a stretch of track extending over approximately 2.5 kilometres. CEMEX fitted the elastic bearings to the concrete sleepers directly in its sleeper factory. London Underground itself fitted the pads to the timber sleepers.

Structure-borne noise measurements taken following the installation verify the effectiveness of the vibration protection solution. "A significant reduction in groundborne vibration has been achieved in a number of neighbouring properties. Some long-term residents living next to the track have even written and thanked us for providing them with greater peace and quiet". Additionally, the sleeper pads supplied by Getzner required no changes to the installation programme, methodology or equipment for the track renewal. "Overall, the use of Getzner sleeper pads on this project has been a great success", stated Mike Barlow, Principal Project Engineer from London Underground.

Other successful vibration isolation projects with USP in the UK include the Birmingham Arena Tunnel and numerous projects with turnouts and other track sections with special requirements.

SUMMARY

Under Sleeper Pads are a state-of-the-art technical solution reducing both lifecycle costs as well as reducing vibrations in railway tracks. Being already a standard product in countries like Austria, Germany, France and Italy, in recent years the positive effects of USP demonstrated also led to introduction of these elastic elements in the UK.

As of 2018 more than 200.000 sleepers in the UK (mainline and urban railway) have been equipped with polyurethane USP. The biggest number of these USP have been installed for LCC reduction reasons; a smaller number for vibration isolation purposes. This development can also be observed worldwide, as the adoption of USP into best practices for railway superstructure construction continues to spread across all continents.

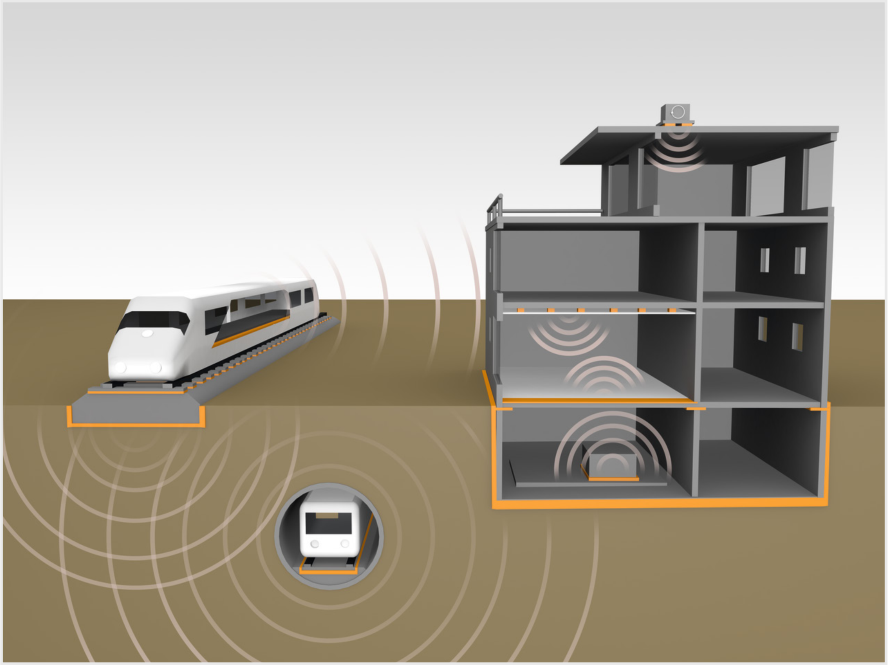


Figure 8: Vibrations and structure-borne noise in the surroundings of railway lines

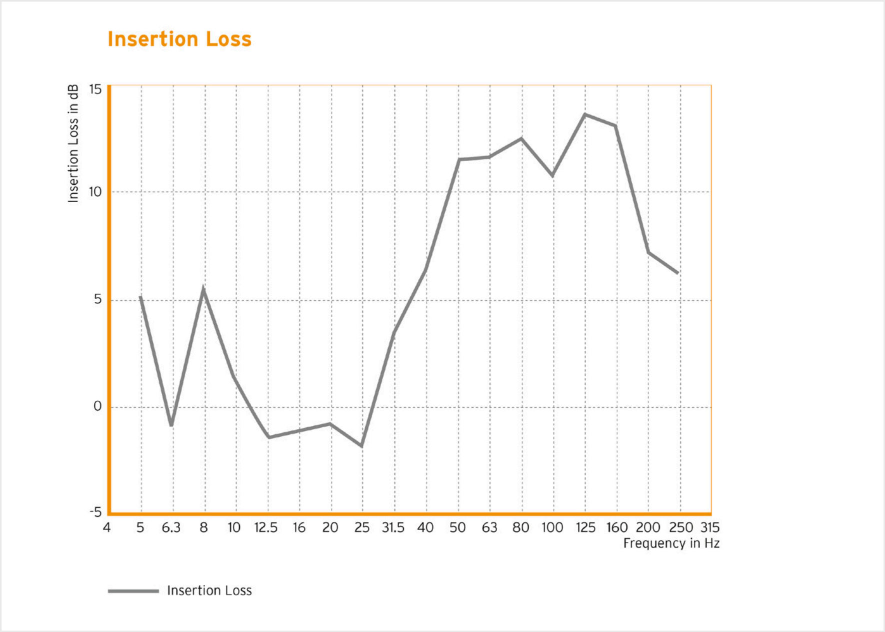


Figure 9: Measured insertion loss curve of superstructure with USP in Krakow, Poland

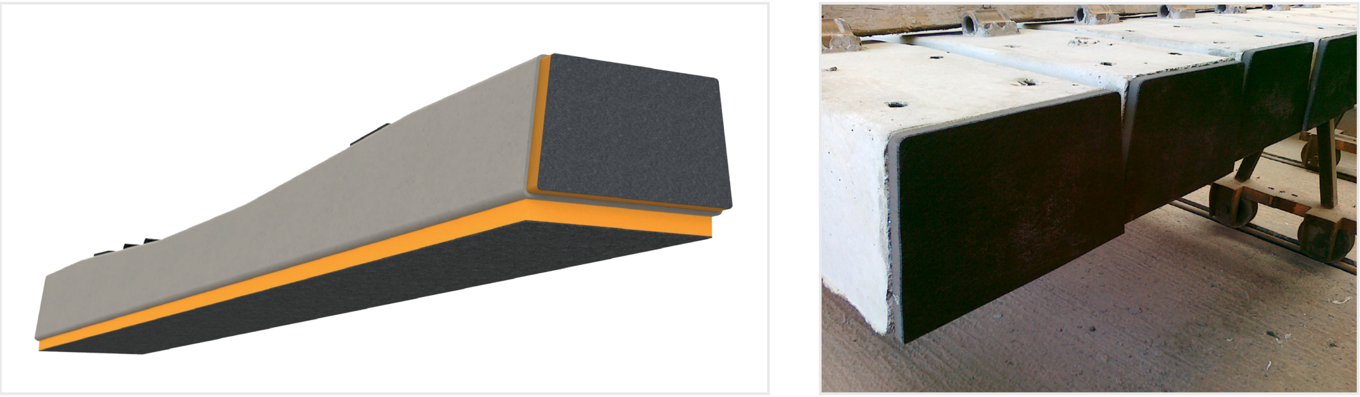


Figure 10: concrete sleeper with USP including a special elastic bearing on both front ends of the sleeper for additional vibration isolation (left: schematic 3D image, right: photograph).

To sum up all theoretical calculations and practical experiences, it can be stated that only concrete sleepers with Under Sleeper Pads fulfil the demand for a more sustainable and cost effective superstructure.

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