NON-BALLASTED TRACK FOR THE NOISE & VIBRATION REQUIREMENTS OF TOMORROW

Martin Fink
Sonneville AG
Industriezone 2, 3225 Muentschemier, Switzerland
Tel: +41 32 312 98 56 Fax: +41 32 312 98 88; Email: martin.fink@sonneville.com

Peter Laborenz
Sonneville AG
Industriezone 2, 3225 Muentschemier, Switzerland
Tel: +41 32 312 98 09 Fax: +41 32 312 98 88; Email: peter.laborenz@sonneville.com

Ingmar Stoehr
Sonneville AG
Industriezone 2, 3225 Muentschemier, Switzerland
Tel: +41 32 312 98 93 Fax: +41 32 312 98 88; Email: ingmar.stoehr@sonneville.com

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ABSTRACT

Together with Japan, Switzerland was one of the first countries 50 years ago to begin developing a non-ballasted track system, with the particular aim of providing long Alpine tunnels with a maintenance-free and durable track system, which offers a high level of availability of the track infrastructure. Swiss Federal Railway (SBB) selected a track system consisting of reinforced concrete bi-block-sleepers connected by a steel angle bar and encased with a rubber boot at the bottom and a resilient pad to create the necessary elasticity.

In this respect, the system has been continuously further developed and improved with the first milestone being the development of the bi-block system LVT without the connecting bar between the blocks. This huge step enabled its use in the Channel Tunnel between England and France and further developments have brought the system to the next level. The most significant being the development of LVT High Attenuation system with an increased level of noise and vibration attenuation that could even replace light mass-spring-systems. The proven track record as well as easy maintenance and noise and vibration advantages offered by this non-ballasted track system cover tomorrow's general project requirements.

Keywords: Non-ballasted track system, noise and vibration attenuation

1. INTRODUCTION

More than 50 years ago, development of a non-ballasted track system began at Swiss Federal Railways (SBB). It was aimed at offering a durable and low-maintenance type of track system for the long rail tunnels in the Swiss Alps. Together with Japan, where the J-Slab system development started in the 1960s, Switzerland can look back on many years of experience in non-ballasted track technology, which, in consideration of the increasing volume of traffic and maximum availability of the infrastructure, is gaining more and more in significance.

Based on the embedded bi-block-sleeper from the 1960s, the single-block LVT system (see Figure 1) was developed and was installed in the Channel Tunnel between England and France in the early 1990s. The presentation shows the steps of the LVT development from the initial idea through various projects with improvements to the standard system, the development of LVT High Attenuation and LVT for switches and crossings to the current installation in the Gotthard Base Tunnel (GBT), the longest railway tunnel in the world which has started revenue service in June 2016.

2. THE HISTORY OF NON-BALLASTED TRACK IN SWITZERLAND

Given the significance of north-south transit rail traffic, in November 1963 an expert committee was given the task of examining different projects and requirements for Switzerland. Very early on it was clear that only a non-ballasted track system should be considered for the long Alpine tunnels. A system sketch for non-ballasted track was created in the Construction Department at SBB head office in May 1964.

In parallel with French Federal Railways (SNCF), where Mr. Roger Sonneville was in charge for track development, a system based on bi-block sleepers was chosen. The underside of which has been encased in rubber boots, in which a resilient block pad provides the elasticity of the track, and isolates the sleeper from the cast-in-place concrete into which it has been embedded.

In this respect, the following requirements had to be complied with:

- Choice of track components, which were already well known to the track manager in everyday maintenance work,
- Achieving the required vertical track deflection and track elasticity,
- Interchangeability of all components by future proofing and
- Simple track construction with a facility for checking and correcting the position before embedding in concrete.

As no dynamic modelling or laboratory testing of non-ballasted track forms were available at the time, all observations were carried out on a ‘trial and error’ basis either by using test tracks with special trains or installing test sections of non-ballasted track within existing operational lines.

The first short trial track was installed during the construction of the Bözberg Tunnel in the SBB network in 1966 [1]. The entire project was a huge success and showed that the non-ballasted track design worked out as expected even in the long run. A next large scale trail had been carried out in 1974 with the installation of the non-ballasted track with the so called "Bözberg Tunnel system” in the new twin-track, 4.8 km (3 miles) long SBB Heitersberg Tunnel [2], [3].

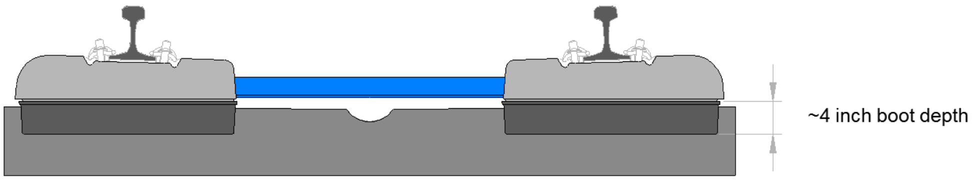


FIGURE 1 Cross-section of original bi-block sleeper for Bözberg Tunnel

The exchangeability of the rubber booted system was proven in 2014 when the first track of the Heitersberg

Tunnel had to be restored. The filling concrete was still in good shape, so only the sleepers had to be exchanged. The exchange of the bi-block sleepers was also due to the significantly increased annual loading over the last 40 years and that a larger rail profile should be used in track.
Working in short night breaks in with an average of more than 100 meters/night, the old bi-block sleepers, including the elastic components, were replaced by new bi-block sleepers B12, specially developed for the project. Compared to the former design, the overall dimensions of these B12 sleepers were slightly smaller at the embedded part and the steel angle between the blocks was replaced by two round bars. After the sleepers had been changed on the complete track length, it could be put back into operation at a full line speed of 140 km/h (87 mph). No subsequent track geometry corrections or concreting work had to be carried out [4].

3. THE DEVELOPMENT OF LVT

3.1. LVT Standard

Based on the good experience in the Heitersberg and Bözberg Tunnel, the system was installed worldwide in several projects. In Switzerland the system went through a modification to make the system safer for people walking the track for maintenance or in case of an emergency. In the Zurich Airport train station the tie bars connecting the two blocks were removed after the track was constructed. This solution added an unobstructed passway and easier cleaning to the track but partly resulted in slightly gauge widening, which was still within the tolerance range [5].
For the Channel Tunnel project, the tolerances for gauge widening were very strict. Due to the good performance of the modified Bözberg bi-block-sleeper, Mr. Roger Sonneville came up with the idea to eliminate the connection bar entirely and therefore create a 50% deeper embedment of the supports compared to the bi-block version.

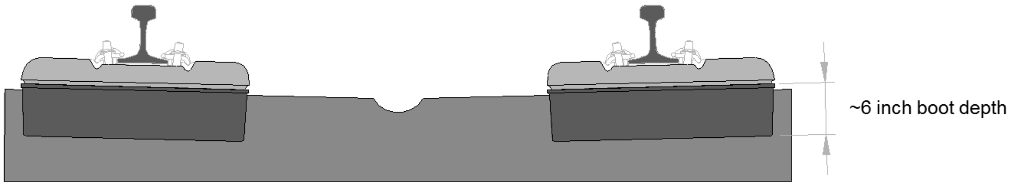


FIGURE 2 Section LVT Standard

In 1989 this new non-ballasted track system was prequalified to be tested at the Technical University in Munich, besides two other systems, Stedef from France and PACT from the UK. All three systems had been tested for compliance with the specifications for this high-profile project. The choice of LVT was based primarily on its very low Static/Dynamic ratio in the tests carried out on assembled rail support blocks as well as the huge cost savings from the use of mass concrete in the trackbase without any reinforcing. A key element in the LVT non-ballasted track system is the use of 'double resilience' in its rail supports, i.e. two distinctive resilient components: the microcellular pad with a low stiffness located below the concrete block and a rail pad with a slightly higher stiffness between the rail and the block.

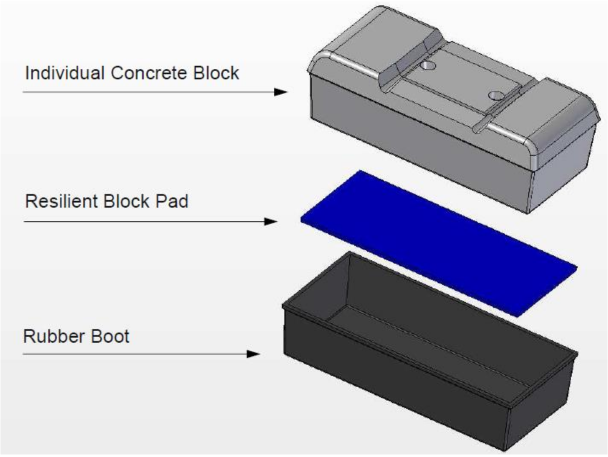


FIGURE 3 LVT Components

Besides the resiliency the LVT supports also generate a homogeneous load distribution in the entire track. Therefore the loads deriving from the train and transferred into the concrete result in small stresses. Hence reinforcement in the filling concrete is not necessary to handle the loads.

In the meantime LVT has proven its choice by keeping the gauge widening within the tolerances and also ensuring an exceptional maintenance performance. The LVT non-ballasted track system in the Eurotunnel has accumulated more than 2 billion gross tons over the last 20 years in service challenging harsh environmental conditions and high daily rate train loading.

The design of the non-ballasted track in the Swiss Zimmerberg Tunnel, which is part of the New Railway Link through the Alps (NEAT) and designed for a train speed of 200 km/h (125 mph), is characterized by the absence of any structural reinforcement in the LVT non-ballasted track system as well as in the concrete sub-layers.

3.2. LVT High Attenuation

With the success in the Eurotunnel project, LVT received a worldwide recognition and was installed in a number of railway projects throughout the world. With the worldwide urbanization, reliable public transport has become more important. In order to avoid traffic congestion on the surface, local authorities plan new lines underground. This creates the problem of ground-borne-noise. Although LVT already provides an efficient level of noise and vibration mitigation, some areas call for a higher level. Up to the 1990s the solution for this problem was solely the use of mass-spring-systems/ floating slabs. Although the performances of these systems in noise and vibration mitigation were excellent, the maintenance is difficult. In case the spring/ resilient mat has to be replaced due to wear or malfunction, the entire slab has to be lifted, which is a technical challenge, time consuming and expensive. As an alternative for light mass-spring-systems, Sonneville developed the LVT High Attenuation system (LVT HA). The track can be maintained in the same way as the LVT Standard system, without the use of heavy machines, but providing a higher level of protection against ground-borne-noise and vibrations than other non-ballasted track systems.

3.3. LVT Traffic

With LVT traffic, vehicles with pneumatic tires can also run on the non-ballasted tracks. The general characteristics of the LVT system, like noise- and vibration mitigation and easy maintenance, are also ensured with LVT traffic.

Modern rescue concepts are frequently based on vehicles running on pneumatic tires going into tunnels. In the LVT traffic system an additional cast-in-place concrete layer and newly developed LVT supports, which have high shoulders and can be separated from the cast-in-place concrete layer with special developed formwork covers, allow the use of pneumatic tired rescue vehicles on the tracks. This means that LVT traffic displays the same exceptional behavior in terms of track deflection and vibration mitigation as all previous LVT solutions.

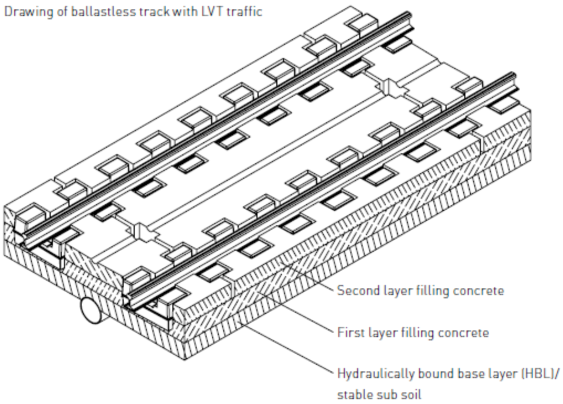


FIGURE 4 LVT traffic

4. LVT DYNAMIC TESTING FOR GOTTHARD BASE TUNNEL

Given the anticipated extraordinary stresses on the track components in the Gotthard Base Tunnel, they had to undergo extensive testing before they could be incorporated. The main aspects in this respect were durability and a long service life.

The high temperatures of around 40°C and high air humidity of approximately 70% in the tunnel pose extraordinary climatic demands, added to which are an anticipated track loading of 0.5 million tons per day, with a maximum axle load of 25 tons.

Hence an essential part of the test program, which was carried out at the Technical University of Munich, were repeat load cycle tests in excess of 10 million load cycles, during which the ambient temperature to be expected in the tunnel was simulated.

FIGURE 5 Test set-up laboratory

These tests were broken down as follows:

- Determination of the baseline static and dynamic (1 -15 Hz) system modulus of rigidity before the dynamic fatigue testing. Two different angles of inclination were tested; test specimen with no horizontal angle (0°) and test specimens with a 22° angle (22°).
- Dynamic fatigue test with 10 million cycles, with a test specimen / load application angle of 22° at a temperature of 40°C, in order to simulate the worst-case temperature conditions that are predominant in the Gotthard Tunnel
- Determination of the system rigidity moduli after the dynamic fatigue test and comparison of the values determined.

The test specimens exhibited support stiffness between 28.4 kN/mm (load application vertical, static) and 43.7 – 50.0 kN/mm (load application under - 22°, dynamic). The requirements of the ATG tender with regard to static stiffness of > 25.0 kN/mm with a horizontal testing orientation, as well as a dynamic stiffness of < 55.0 kN/mm with an inclined orientation were very well met.

During the dynamic fatigue test, both test specimens set-ups (0° and 22°) were incorporated into the test machine simultaneously. Once the required temperature of 40°C had been reached, 10 million load cycles were applied, which had a vertical load component impact of 60 kN per support. One requirement of the endurance test according to the tender specifications was the amplitude or the change in displacement amplitude < 20 % from cycle 10^2 to 10^7. Another requirement was the wear of the resilient components. Neither the block pad nor the rubber boot should show points that are worn through, whereas the boot must not show wear of any more than 50% of the wall thickness at any point compared with its new condition. Both criteria were most certainly fulfilled by the test specimens being examined. Equally, a visual examination of the track system components after 10 million load cycles revealed only slight signs of wear resulting out of initial adjustment effects or possible restraints.

Working on behalf of the consortium, ARGE Fahrbahn Transtec Gotthard (AFTTG), Stans (Switzerland), following on from multiple trial runs in February and March 2014, dynamic deflection measurements were carried out in the Gotthard Base Tunnel during two test periods:

- 20 - 21 February 2014 with deflection measurements under an RE 420 at running speeds of 10 km/h (6 mph), 80 km/h (50 mph) and 120 km/h (75 mph),
- 11 - 13 March 2014 dynamic deflection measurements under 2 x RE 460 + 3 brake vans + 1 driving trailer simultaneously with measurements for traction current supply at speeds of 160 km/h (100 mph), 180 km/h (112 mph), 200 km/h (125 mph) and 220 km/h (137 mph).

The runs took place in the western tunnel close to transverse tunnel 150, which lies about half-way along the approximately 13 km (8 miles) long Faido – Bodio test track. During these tests, the same instrumentation was arranged on the inductive displacement transducers at three cross-sections (left and right rails) as in laboratory tests (see Figure 6). Measurements were taken automatically during the two sets of trials and also monitored and saved on a computer at IP Biasca via a network link.

FIGURE 6 Test set-up track

Figure 7 shows the rail deflection measurements when running over the instrumented track section in the 2nd test campaign at a speed of 220 km/h (137 mph) at measurement cross-section 2. A 100 Hz low pass filter was used to analyze the signals. A 100 Hz low pass filter was used to analyze the signals. Figure 8 shows the average value of the maximum rail deflection under the locomotive axles for the test runs at the respective speed levels.

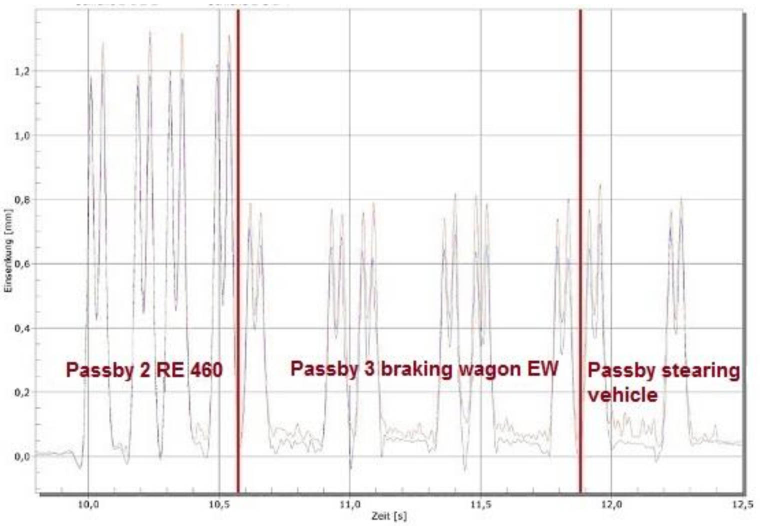


FIGURE 7 Deflection measurements

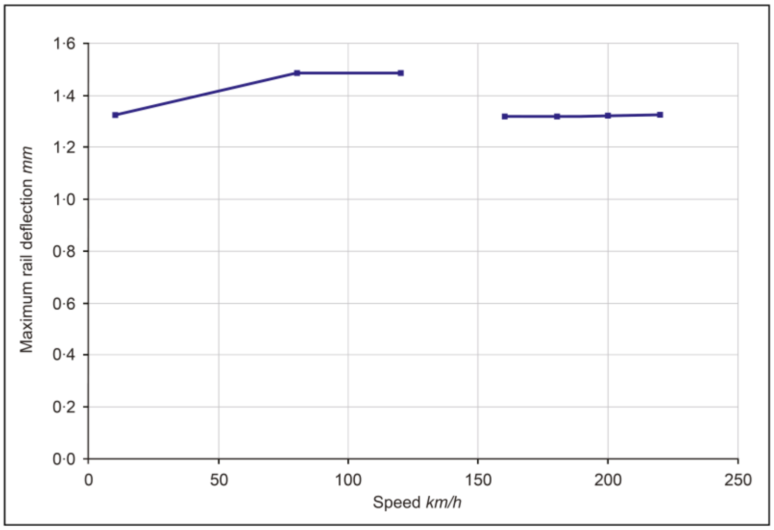


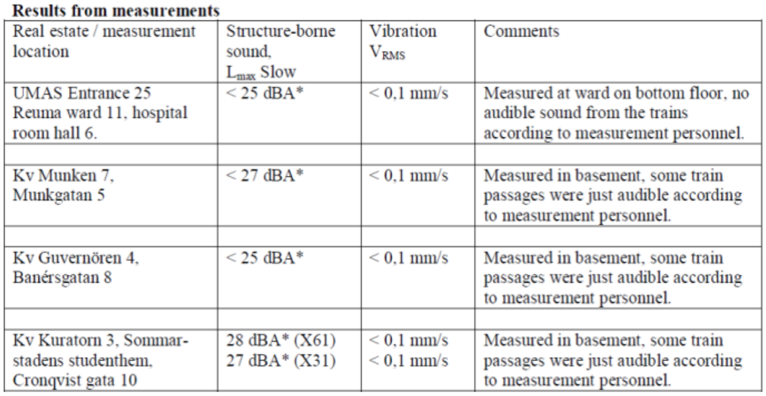
FIGURE 8 Deflection measurements

With regard to the dynamic deflection measurements, in summary it can be established that the rail deflection at the measured LVT support points remained virtually unchanged at approximately 1.3 mm (0.05 in.), under both quasi-static and dynamic loading. The larger deflection measured at running speeds of 80 km/h (50 mph) and 120 km/h (75 mph) can be attributed to the dynamic influences of the loading vehicle which have a greater effect on the deflection curve than the stiffening of the elastic material. A stiffening of 1.3 times, which was determined in laboratory trials in 2010, had been confirmed with the field measurements.

5. NOISE AND VIBRATION MEASUREMENT WITH LVT-HA

5.1. LVT-HA Noise and vibration study Citytunnel Malmö, Sweden

After the installation of LVT HA in Los Angeles (Gold Line) and London (East London Line), the system was installed in the Citytunnel of the Swedish city of Malmö. The tunnel underpasses some sensitive areas and the initial solution for the track system was a kind of light mass-spring-system. Sonneville AG could prove that the use of LVT HA would keep the noise and vibration within the specified limits of v < 0.4 mm/s and 30 dBA. The authority accepted the change in design after evaluating the provided calculated results of a vibration attenuation model. The LVT HA system had been installed on the complete length of the 6 km (3.7 miles) long double track tunnel. After the completion of the project extensive measurements in several locations in basements above the tunnel were executed by an external acoustics bureau. The table below shows the results of the measurements.



Results from measurements

Real estate / measurement location	Structure-borne sound, L_{max} Slow	Vibration V_{RMS}	Comments
UMAS Entrance 25 Reuma ward 11, hospital room hall 6.	< 25 dBA*	< 0,1 mm/s	Measured at ward on bottom floor, no audible sound from the trains according to measurement personnel.
Kv Munken 7, Munkgatan 5	< 27 dBA*	< 0,1 mm/s	Measured in basement, some train passages were just audible according to measurement personnel.
Kv Guvernören 4, Banérsgatan 8	< 25 dBA*	< 0,1 mm/s	Measured in basement, some train passages were just audible according to measurement personnel.
Kv Kuratorn 3, Sommar-stadens studenthem, Cronqvist gata 10	28 dBA* (X61) 27 dBA* (X31)	< 0,1 mm/s < 0,1 mm/s	Measured in basement, some train passages were just audible according to measurement personnel.

FIGURE 9 Measurement results LVT HA

As described in the table, some passing trains were only noticeable by the instruments and the personnel did not hear or feel anything.

Additionally in 2014 the insertion loss (IL) of the LVT HA system relative to a normal ballasted track in Citytunnel in Malmö was measured. The results show that the measured IL of the LVT HA system compared to the ballast track is about 31 dB at 63 Hz in the cut-and-cover tunnel (section B) and about 26 dB at 63 Hz in the drilled tunnel (section A). For every noise sensitive project an expected theoretical insertion loss (IL) calculation can be provided. For the project in Malmö the calculated IL was about 21 dB at 63 Hz. The diagram below shows that the measured IL is higher than the calculated IL at almost all 1/3 octave bands of interest (31.5-200 Hz) and verifies the data basis used for the IL calculation.

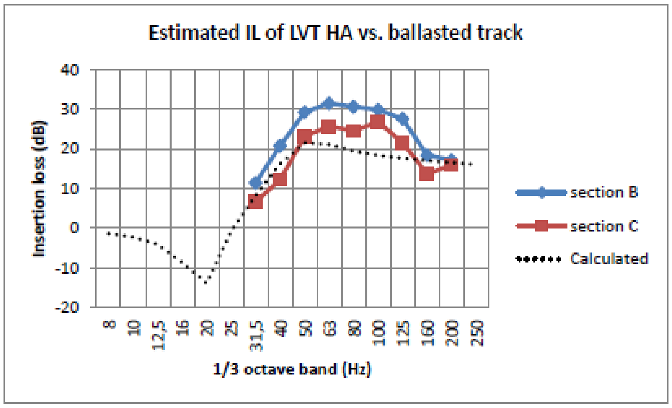


FIGURE 10 Insertion lost measured/calculated

5.2. LVT-HA study for Los Angeles Metro "Little Tokyo"

In February 2016 Construction Polymers, the North American licensee of Sonneville AG, commissioned ATS Consulting to perform a series of field tests and computations to determine the effectiveness of using the LVT-HA system as a vibration mitigation measure on the LA Metro Regional Connector Project. The track section passing under an area known as "Little Tokyo" has been designed with stringent noise and vibration mitigation requirements. The initial design utilized a mass-spring-system with direct fixation. The goal of the testing was to determine whether the LVT-HA system was sufficient to keep ground borne noise levels inside building adjacent to the Little Tokyo portion of the alignment below the limits that have been used for the Regional Connector project. The required data was collected from measuring the transfer mobility and train vibrations at three locations on the Metro system, two on the Gold Line (LVT Standard and LVT-HA low profile) and one on the Expo line (rubber bonded DF). Additional data from LVT and DF measurements in the same areas was gathered from previous measurements done by Wilson Ihrig in 2009 and was used for comparison to the recently commissioned testing.

At first sight the results obtained by ATS were acceptable overall, but for Sonneville AG they were not a satisfactory. Especially the difference between the DF and LVT-HA section were only marginal. So comparing the measurements from 2016 with those received in 2009, the DF section showed similar values in both tests, whereas a significantly higher FDL (force-density-level) of up to 20 dB was detected in both LVT areas of the ATS measurements.

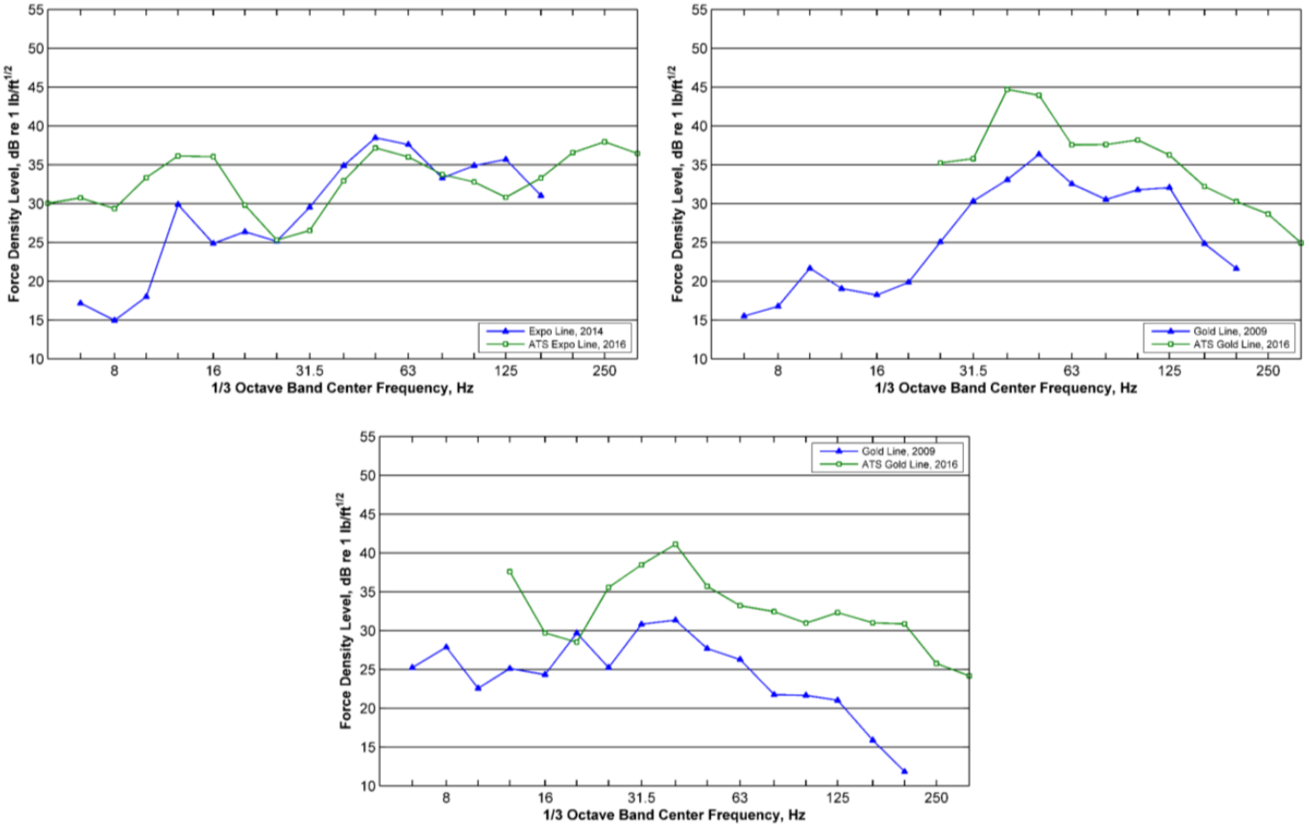


FIGURE 11 Force density curves for DF (upper left), LVT Standard (upper right) and LVT-HA track, comparison between measurements 2009/2014 and 2016

Rail roughness, the most likely cause of the higher FDL, could be excluded as it was measured in both years and was found to be comparable. Other reasons could not be found, so the approach was to verify that the performance of the LVT system has not decreased or the system has any internal degradation. An insertion loss calculation for both LVT standard and LVT-HA showed similar results to the ones from 2009 and the

shape of the FDL spectrums for both LVT tracks are similar to previous measurements. These two points and also the numerical models support the conclusion that the systems are operating in a dynamically similar fashion and that the system is suitable for the use in the Little Tokyo area.
Although the results show a sufficient noise and vibration attenuation from the previously installed LVT-HA in the Gold Line (support stiffness 8kN/mm) also for Little Tokyo, Sonneville was asked to add some safety margin to the LVT HA supports in terms of noise and vibration reduction. Sonneville AG therefore designed a LVT HA support a support stiffness of around 6kN/mm, the lowest stiffness ever developed for a project. With this ultra-soft LVT-HA support an additional 5dB was added to the noise and vibration attenuation, as can be seen in the figure below.

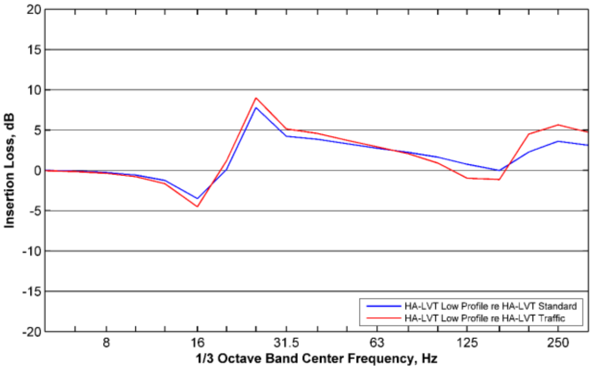


FIGURE 12 Insertion loss of HA-LVT Low Profile (100 kg, 8 kN/mm) relative to standard (125 kg, 6 kN/mm) and Traffic (160 kg, 6 kN/mm) versions of HA-LVT

The idea of adding additional weight to the support by using an LVT traffic block only showed a marginal benefit (red line) and was not considered a suitable and economical solution.
Nonetheless the measurements show, that the very soft LVT-HA system is a viable solution for the “Little Tokyo” area and possibly could also replace some light mass-spring-system areas in the LA Metro purple line.

6. FUTURE DEVELOPMENTS

As far as the further development of non-ballasted track is concerned, it is planned by various authorities to not only use the non-ballasted track system in tunnels, but in general wherever a rigid track subgrade exists. Therefore in Switzerland two bridges 394 m and 1,156 m long, which are part of the Zurich Cross-City Link, had been the first long bridges to be equipped with LVT in Switzerland. In other countries such as Brazil and England and also in New York and Chicago, bridges have already been equipped with LVT and have proven their economic and technical advantages. At the same time, developments, especially for railway projects in urban areas, are moving forward with the aim of finding a non-ballasted track system which offers improved protection against vibrations
Another development is going in the direction of replacing existing ballasted tracks in tunnels and on bridges with non-ballasted track, and ideally when still in operation so as to cause minimal interruption to the infrastructure. In particular in Switzerland with a large number of tunnels and a high density of traffic only offering a small window for maintenance work, this is an important aspect which should be kept under scrutiny in the coming years.

7. CONCLUSION

Effective noise and vibration attenuation is one of the key figures of the Low Vibration Track (LVT) system. As the measurements in Malmö and LA show, LVT-HA can be a very economical solution for enhanced noise and vibration mitigation and can even replace a light mass-spring-system and outperforms the typical egg-fastener systems. The economic benefit not only derives from the easier installation, but also the maintenance, which is only a fraction in costs and time compared to floating slabs over the expected life-time of 50 years.

As the past has shown, the further development of the LVT non-ballasted track system and process to install it, requires close cooperation between industry and rail operators, so as to achieve the best possible result and to obtain the overall Sonneville credo: ***"Make everything as simple as possible, but not simpler"*** (Albert Einstein).

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