**RIVAS Report Summary**

Project ID: 265754  
Funded under: FP7-TRANSPORT  
Country: France

---

**Final Report Summary - RIVAS (Railway Induced Vibration Abatement Solutions)**

**Executive Summary:**
RIVAS project for innovative vibration mitigation technologies

Rail traffic and in particular rail freight transport is promoted as the most sustainable way of surface transport within the European Union. However, noise and vibration are often perceived as weaknesses in rail’s environmental credentials. While noise is an issue for all modes of transport, vibration is specific to rail. In the case of new lines, vibration mitigation already features heavily in the cost of making them acceptable to the public.

**Focus of RIVAS**

RIVAS (Railway Induced Vibration Abatement Solutions) is a three years lasting collaborative rail research project co-funded by the European Commission that aims at reducing the environmental impact of ground-borne vibration from rail traffic while safeguarding the commercial competitiveness of the railway sector. For several areas of concern innovative technologies shall be developed allowing for reduction of vibration in residential areas near railway lines to values to near or even below the threshold of perception.

RIVAS' focus is on low frequency vibration from open lines which is a concern mainly for freight traffic. However, RIVAS results will also be applicable to suburban, regional and high-speed operations.

RIVAS concentrates on the development of an integrated system of practice-orientated technologies for the reduction of vibrations emitted from passing trains at or close to source.

Railway induced ground borne vibrations result from the interaction between a moving rail vehicle, the track superstructure and the subsoil. This system of vehicle, track and soil represents the source of ground borne vibrations. This source interacts with the surrounding soil. The project examines all vibration effects and aspects of the whole system, which is well reflected in the project structure. It includes fundamental research, prototype construction, optimisation of already existing solutions and field testing under realistic conditions.

**Project Structure**

Four Work Packages (WP) focus on the sub-systems vehicle, track, soil and their interfaces. A separate WP is dedicated to the definition of measuring procedures, and procedures to predict exposure in buildings and annoyance.

WP1 establishes the test procedures to monitor and control the performance of vibration mitigation measures under realistic conditions.

WP2 develops and evaluates mitigation measures based on reducing the excitation of vibration at the vehicle-track interface by improved maintenance.

WP3 develops and evaluates mitigation measures for ballasted and slab tracks.

WP4 develops and evaluates mitigation measures based on sub-grade improvement and ground barriers within the railway...
WP5 addresses the impact of the vehicle
Each of the solutions is to be validated with field tests on the major European rail networks represented in RIVAS.

Project work in RIVAS can be divided into three phases. Phase I defines priorities for the R&D activities based on state-of-the-art reviews, design studies, computer simulation and the analysis of existing data. Phase II focuses on development of new vibration reduction technologies and optimization of existing solutions, which includes computer simulation, prototype construction and laboratory testing. The final phase III is devoted to field testing of the products and strategies developed in phase II under realistic conditions.

Project Context and Objectives:

Project context

Ground vibration from railway traffic is generated either by the static axle loads moving along the track or by the dynamic forces arising from wheel and track irregularities. The influence of vehicle parameters like e.g. wheel set mass, axle distances, and properties of primary and secondary suspension has been quantified in a combination of state-of-the-art numerical modelling using train-track-soil models and the analysis of measurements. A similar research has been done to study the influence of wheel defects (most notably wheel flats and wheel polygonalisation) and of track irregularities. As the transmission of vibrations to receiver locations and also the performance of vibration mitigation measures strongly depend on the soil conditions, existing sites have been chosen as reference, where soil conditions are well known. These are located in Germany, Belgium and Sweden. Design studies and numerical modelling of the influencing parameters are performed within RIVAS such that they finally predict vibration levels at hypothetical receiver locations at the reference sites in order to ensure maximum comparability. In phase II and III of RIVAS, vibration reduction strategies based on optimized vehicle design and optimized maintenance of both wheel and track have been worked out and tested.

Low vibration track design requires reducing the global stiffness of the track. Parametric studies have been performed using coupled Finite Element/Boundary Element models both for ballasted track and for slab track. Various modifications of the rail-sleeper interface as well as of the sleeper-ballast interface (sleeper-slab interface in the case of slab track) have been simulated taking into account different types of soil and of rolling stock with the overall target of vibration reduction. Designs of wide sleepers in combination with soft under sleeper pads and of rail fastening systems with soft under rail pads have been proposed as being the most promising solutions. Corresponding systems were tested in laboratory in phase II of RIVAS. Field tests were performed in phase III. Solutions especially dedicated to reducing vibrations emitted from curves and switches could be achieved.

Vibration reduction measures on the transmission path between track and receiver (analogue to noise barriers) are ideal candidates for retrofitting existing lines as their installation does not require closing the track. Within RIVAS several designs have been studied by computer simulation: soil stiffening and sheet pile walls close to the track, open trenches and trenches filled either with soft or stiff materials. Their effect has been predicted for the reference cases (see above) and for two sites, where installation and field testing could be performed within RIVAS – phase III. For the latter sites, design optimization has been performed for the relevant frequency range taking into account soil layering. The potential field test sites, which are located in Spain and Switzerland, have been characterized by geotechnical tests.

In order to make measurement results comparable, reference conditions with respect to vehicle, track and soil have been stipulated. Clear procedures have been worked out for transferring data measured within RIVAS under non-reference conditions to reference conditions and vice versa. Typical “hotspots” in Europe with existing vibration problems have been defined in terms of traffic, building types, soil, and number of residents affected but also in terms of legal requirements. Based on appropriate descriptors for assessing annoyance of residents inside buildings by vibrations, these cases were used at the end of the project for the final proof of the efficiency of mitigation measures developed within RIVAS.

RIVAS Consortium

The RIVAS project is strongly end-user driven in order to ensure an utmost exploitation of results in practice and to prepare an extensive and fast implementation of technical developments. The RIVAS consortium comprises 27 European partners, among them infrastructure managers, manufacturers, suppliers, universities and research institutes, led by the International Union of
Railways (UIC).

Project objectives

RIVAS’ mission is to reduce the environmental impact of ground-borne vibration while safeguarding the commercial competitiveness of the railway sector. It therefore aims to contribute to relevant and world leading technologies for efficient control of people’s exposure to vibration and vibration-induced noise caused by rail traffic. These technologies will be applied to vibration ‘control at source’ (improved maintenance of track and wheel as well as rolling stock and track) and vibration mitigation on the transmission path. RIVAS also includes effects at the receiver location (i.e. annoyance and exposure of residents to vibrations). The focus is primarily on freight traffic. Nevertheless solutions will be applicable to other rail sector operations (local (suburban), regional and high-speed networks.

Efficient vibration mitigation requires:

1. A toolbox of efficient vibration reduction technologies (rolling stock/ track/ transmission) for a wide variety of applications;
2. Clear procedures for the assessment of the effect of vibration reduction technologies both in terms of physical parameters and human perception.

RIVAS reflects this by combining technical innovation with the development of unified measurement and assessment procedures. Its main objectives are therefore the development of technologies to reduce vibration at source and the development of cost effective test procedures including a measurement protocol to monitor and control the performance of vibration reduction measures, hence making results comparable throughout Europe. The focus is on measures that can be implemented on existing lines (retrofit). They will be applicable to

- rail vehicle design;
- rolling stock maintenance;
- track design;
- track maintenance;
- sub-grade engineering;
- the transmission path within the railway infrastructure.

Selected vibration mitigation measures were designed, installed on real tracks and their performance assessed in field tests.

The key deliverables of the project are:

- Definition of appropriate procedures to predict exposure in buildings and estimate corresponding annoyance (D1.6);
- Classification of track (D2.1) and wheel (D2.2) conditions with respect to vibration emission;
- Results of the parameter studies and prioritisation for prototype construction for ballasted track and for slab track (D3.2);
- Conclusions of parametric study affecting field tests for vibration mitigation measures on the transmission path (D4.2);
- Characterisation of vehicle parameters from test data and numerical analysis (D5.2);
- Best-practise Workshop “Vibrations - Annoyance, Acceptance and Assuming the challenge to find solutions” (D6.3);
- Final report on the reference track design for vibration characterisation of vehicles including draft measurement guideline for vehicle homologation (D1.8);
- Benchmark tests for soil properties including recommendations for standards and guidelines (D1.11);
- Validation of wheel maintenance measures on the rolling stock for reduced excitation of ground vibration (D2.9);
- Mitigation measures installed on commercial track (D3.5);
- Guidelines for mitigation measures on ballasted track, curves, switches and slab track (D3.13);
- Final report on the reference track design (D3.15);
- Conclusions of numerical study of all transmission mitigation measures (D4.4);
- Design guide and technology assessment of the transmission mitigation measures (D4.6);
- Guideline for Design of Vehicles Generating Reduced Ground Vibration (D5.5);
- Field test measurement report – the influence from vehicle design on the generation of ground-borne vibration (D5.6);
The main objectives of the second period were design studies, computer simulations and field tests of mitigation measures. With parameter studies the components with the highest vibration reduction potential could be identified. Measurements (in particular free field measurements and soil properties) have been performed due to the RIVAS measurement protocol to ensure compatibility of results obtained by different partners under different boundary conditions. Beside the validation of the mitigation-measure efficiencies, the field tests have shown that the simulations performed mainly in the first period of the project give good results and can be used for the prediction in the future. The experiences obtained during the project were included in guidelines focussed on the practical aspects to be considered when applying mitigation measures in the track, at the propagation path and at the vehicles. In addition, the effects of all mitigation measures developed were shown in terms of annoyance reduction for different ground-building configurations.

Project Results:
Description of the main final project results presented by each technical work packages

Since future transport requires a system that is able to move a lot more passengers and freight than it is today, a high-capacity, efficient, cost-effective and environmentally friendly transport system is necessary across Europe. The Strategic Rail Research Agenda 2020 of the European Rail Research Advisory Council (ERRAC) expects rail transport to double. However, an increasing number of people living near railway lines are annoyed by noise and vibrations as side-effects of rail transport, hence it is necessary to find ways to reduce those effects. Thus over the three years of its duration, the RIVAS project tackled the challenge of developing and analysing vibration mitigation measures - under the patronage of the European Commission (FP 7). The 27 partners, placed under the coordination of the International Union of Railways (UIC), represent end-users such as infrastructure managers and train operating companies (ADIF, DB, RATP SBB, SNCF, Trafikverket), associations, manufacturers and suppliers (Alstom, Bombardier, EiffageRail, Keller, Lucchini, Pandrol, RailOne, Sateba), universities and research institutes (BAM, CEDEX, Chalmers University, CSTB, ISVR, KU Leuven) as well as consultants and associations (D2S, Satis, TÜV Rheinland, Vibratec, Prose).

WP1 – Assessment and monitoring procedures

The work package supports the development of mitigation measures within the RIVAS project. To reach this aim, measuring procedures, calculation tools and routines to assess annoyance were provided allowing the comparison of results obtained by different partners.

To detect mitigation-measure efficiencies, advanced measuring protocols based on train pass-bys and artificial excitation were developed. By using a combined procedure, the vibration levels are measured in the test section and the reference section at a certain distance from the track before and after the installation of the mitigation measure to get optimal results (Figure 2 - to be found in attached document). In addition, measuring procedures were proposed to detect vehicle, track and soil parameters influencing the vibration reduction significantly. Especially the measurement of soil parameters was in the focus of the investigations.

Here, benchmark tests showed their influence on the efficiency e.g. for mitigation measures in the propagation path. For the exchange of data between the RIVAS partners, a database structure was provided.

For the final presentation of results, a procedure to assess the annoyance inside buildings based on four descriptors (two for vibrations and two for vibration-induced noise) with generalized exposure response curves was proposed. Based on different ground-building combinations and typical hotspot configurations, the results for the mitigation measures developed were transferred to an annoyance reduction and presented with respect to their cost-benefit relation. Based on the typical spread of relevant parameters, a virtual track to be used for the optimization of vehicle design will be proposed as well as calculation procedures.

Conclusion
As a result of our investigations, the use of common measuring protocols was found to be substantial to obtain reliable and comparable results. Influencing parameters have to be detected and are especially needed for the transfer of results from one side to another. In addition, the procedure to calculate the annoyance reduction inside buildings can be used to find the best suited solutions. Virtual test tracks are considered to become an important tool for optimization of vehicle designs in the future.

Measurement procedure based on artificial excitation
For the detection of mitigation-measure efficiencies, a procedure based on vibration measurements during train pass-by was developed within the RIVAS project. But especially for testing the mitigation effect of resilient elements in the track, a measurement procedure with artificial excitation has significant advantages. First, the installation of a new mitigation measure at a test track is possible without performing the full homologation process. Second, installation costs are low because the mitigation measure has to be installed only for some meters instead of one hundred meters as required in the measuring protocol based on train pass-bys.
Therefore an alternative measurement method to detect mitigation-measure efficiencies by using artificial excitation was tested within RIVAS. As seen from previous investigations, the main problem is to include a preload on the track. Because the procedure has to be easy-to-handle, cost-efficient and simple to install and to uninstall in the track, an approach proposed by the engineering company “Ingenieurbüro Dr. Heiland” based on using two excavators for applying the preload was tested. For the vibration generation a special harmonic shaker was used to operate a vibration sweep over a frequency range of 0 – 110 Hz with nearly constant forces. To determine the influence of the preload on the impact of resilient elements, different load configurations can be investigated realized by different positions of the buckets. Figure 3 (to be found in attached document) shows a picture of the experimental setup.

The mitigation-measure efficiency has to be obtained at a measuring position next to the track (e.g. at a distance of 8 m from the track center) at the sections with and without mitigation measure. The difference in the transfer motilities with and without mitigation measure leads to the insertion loss, a parameter of the efficiency. A first test of the experimental setup was done at an existing test site with two different types of under sleeper pads. Keeping in mind that even at the test site with a length of some hundred meters, the soil parameters can vary considerably, a further test is needed to correct the influence of the soil parameters on the mitigation-measure efficiencies. Therefore, an excitation realized by a falling weight was applied on the ballast between two sleepers at the section with and without under sleeper pads. The measured transfer mobility can be used for corrections if needed. Figure 4 (to be found in attached document) shows the results for the insertion loss without and with correction for the test site used. Only with the soil correction, the isolation effect as expected from theory can be seen.

The experiment revealed a very important finding: the measured efficiency depends significantly on the preload. Moreover, the comparison between the efficiencies obtained during train pass-by and by artificial excitation show some deviations which are based on different track irregularities arising with and without under sleeper pads and on different forces influencing the parametric excitation. But it was concluded that the isolation behaviour of different resilient elements in the track can be measured and compared with this method.

WP2 – Mitigation measures at source
The source of vibrations induced in the vicinity of track is the interaction force created at the wheel-rail contact point when a train passes on a track. This force is strongly influenced by the wheel and rail irregularities.
RIVAS Work package 2 has been investigating the vibration levels caused by wheel and track irregularities, in order to propose and discuss maintenance measures to reduce vibrations.
Indeed, vibrations are caused by irregularities in track evenness (longitudinal level, isolated defects, insulated joints, corrugation, etc), in track support stiffness, by parametric excitation (transition zones, hanging sleepers, etc) and by wheel irregularities (out-of-roundness, flats). A classification of the wheel and track defects with respect to vibration emission has been discussed through numerical simulations and measurements. In addition, a classification of the track and wheel defects within the European networks has been carried out regarding their contribution to vibration emission. Measurements and simulations have shown that wheel out-of-roundness (00R) can have a strong influence on the vibrations emitted by some categories of rolling stock. Track geometry defects with wavelengths lower than about 10 m have some influence on the low frequency vibration, but the parametric excitation has to be considered in addition. Isolated defects shorter than 3 m may generate significantly high free-field vibration. Dipped rails at welds and insulated rail joints can generate high wheel-rail impact loads with broad frequency content that lead to high vibration levels. More details regarding track irregularities are provided below.

Longitudinal level misalignments are defined as the mean value of vertical irregularities of the two rails. This type of misalignment is usually measured with specially equipped measuring cars. Longitudinal levels across European networks have been classified on the basis of ORE B176-curves (Figure 5 - to be found in attached document). This classification is used for the mapping of the simulation results.

Track stiffness variation measurement requires special equipment/measuring cars. Measuring track parameters in the loaded case (e.g. measuring longitudinal level misalignments with the help of measuring vehicles) usually leads to an inclusion of the influence of track stiffness variations in the measured data. Within RIVAS, stiffness distribution has been obtained from RSMV (Rolling Stiffness Measurement Vehicle) measurements. Additionally, distributions of track geometry defects on track with known stiffness variations, such as bridges were classified and generally show poorer geometry than on sections without obvious causes for stiffness variations.

Welding of rails in the field may result in a cusp-like discontinuity. Such discontinuities in the rail induce high-frequency vertical wheel-rail contact forces. Simulations carried out within RIVAS (Figure 6 - to be found in attached document) show that for dipped rail, large contributions to the dynamic contact force in the frequency interval 50 - 100 Hz are observed, and that the vibration level increases with an increasing dip depth.

The measurements of these discontinuities are performed using trolley systems or rulers. The dip depth is defined by the maximum distance from a lm-ruler to the dip (see Figure 7 - to be found in attached document), the width of the dip by the distance of the ruler points of support. The angle at the dip bottom can be derived from the angle between two best fit straight lines to the left and right of the minimum over a length of 250 mm. Classifications is made based on depth, semi-span length and rail misalignment, for joints.

The gap width of a rail joint is typically 4 - 20 mm and the height difference (misalignment) between adjoining rails may be in the range of 0 - 2 mm. In addition, on each side of the joint, there may be a dip in the rail. Such defects induce low frequency vibrations, wider gaps creating higher vibration levels.

Finally, a ranking of the relative influence on the overall ground-borne vibration problem of the different types of track irregularities/track defects has been carried out based on the RMS-values at 8 m distance from the track simulated for all classes of track defects used. The frequency distributions of the contributing defects and defect occurrences on the networks have been used to weight the results.

The works regarding track defects tend to show that the longitudinal level misalignments with wavelengths of 0.6 m seem to be the type of track irregularities with the highest overall vibration impact on the network, although the highest vibration levels are found in the vicinity of welds and insulation joints, while wheel OOR are the main influencing factor regarding wheel irregularities. To this effect, it is proposed to introduce a new wavelength band containing wavelengths in the interval 0.5 - 3 m, not covered by typical track measurements today but within the capabilities of most of the IM measurement cars and tools. Measurements are being performed to verify these findings and to quantify the proposed mitigation and they will be published by the end of the project. For more information, please refer to the RIVAS website.
Track design optimization for ground vibration mitigation consists in reducing the global stiffness of the track. Several mitigation measures installed in the track can be used: ballast mat, under sleeper pads (USP) and very soft rail fastening systems.

Within RIVAS Work package 3, several track configurations have been considered to propose relevant mitigation measures:
- Soft under sleeper pads coupled with heavy sleepers have been optimized and specifically produced to be tested on track, for straight ballasted tracks;
- Soft rail pads have been optimized and specifically produced to be tested on track, for straight ballasted tracks;
- Soft under sleeper pads have been installed in curves to appraise their efficiency in terms of ground vibration reduction and their effect on track stability;
- Soft under sleeper pads have been installed on several switches to assess their effect on ground vibration;
- Soft under sleeper pads have been optimized and tested in a specific slab track system, the GETRAC system.

All these systems have been installed on track to be tested. The final results that will allow concluding on their mitigation impact and the collateral effects are under analysis.

Systems for the straight ballasted track
For the straight ballasted track, two different mitigation measures have been specifically worked out. Soft or very soft under sleeper pads under heavy sleepers allow decoupling the upper part of the track (rail + sleeper) with the lower part (ballast + sub-layers), "capturing" the energy in these upper layers and reducing therefore the mobility between the track and the free-field, as shown on Figure 8 (a) (to be found in attached document).

Rail fastening systems, that allow very soft rail pads to be used, imply an increase of the track receptance at the contact point. With a higher rail receptance, the resonance of the wheel-rail interaction force is shifted to the lower frequency ranges, reducing the interaction force for the frequencies above this resonance, as shown on Figure 8 (b) (to be found in attached document).

Within the Work package 3, as a preliminary work a large numerical study taking into account several influent parameters such as rolling stock unsprung mass or ground stiffness, was carried out to enable optimizing track design. It showed that ground stiffness has a minor impact on the efficiency of both of these mitigation measures. Then according to the results of this numerical parametric study, prototypes have been developed and tested in laboratory before being installed in scale 1:1 test rig or on commercial track.

The soft under sleeper pads installation has been designed with the use of heavy sleepers: this system allows decoupling the upper part of the track (rail + sleeper) with the lower part (ballast + sub-layers), "capturing" the energy in these upper layers and reducing therefore the mobility between the track and the free field. The heavy sleepers, with a larger contact area between the sleeper and the ballast, allow keeping a reasonable rail deflexion at the contact point, even with very soft under sleeper pads. Different combinations of soft or very soft under sleeper pads and heavy and wide sleepers (b) have been tested on the Eiffage Rail Test Rig in Herne during spring 2013 as described in Figure 9 (a), with a dedicated excitation system, see Figure 3 (to be found in attached document) of the Work package 1 section. Several data were measured such as ground vibration velocity at 8 m and 16 m, sleeper vibration velocity, rail deflection, ground characteristics... All measurement results were analysed to have a global overview of {soft USP + heavy/wide sleeper} influence on track dynamic behaviour and ground vibration generation.

The second mitigation measure consists in reducing the railpads stiffness. Therefore, dedicated fastening systems that can support very soft railpads have been developed, with a dedicated sleeper. One of these systems, called DFC Valiant, is a
fastening system with two resilient layers as shown on Figure 10 (to be found in attached document), left: a rubber pad (a) is placed between the sleeper and a cast-iron baseplate (b) on which the rail is mounted through a FASTCLIP system including a classic rail pad (c). A wide range of stiffness can be achieved with the DFC Valiant by using different rail-pad/baseplate-pad combinations.

Before being installed on a commercial track, these fastening systems were characterized with dedicated lab tests. These tests have allowed assessing the global stiffness of the all system \{ballast + sleeper + fastening system + rail\} under a realistic load: an excitation at 5 Hz around 60 kN (+/- 10 per cent). The following results were obtained: 560 MN/m for the reference system, 85 MN/m for the DFC. Numerical simulations were then performed with these estimated stiffness. The computed Insertion Losses at 8 m from the track, indicate that the DFC system will be efficient (IL up to 10 dB) for frequencies above 60 Hz.

Insertion loss measurements will be performed after installation of the DFC on a commercial track in autumn 2013 on a Freight corridor in the East of France. They will allow concluding on the DFC efficiency, confirming or questioning the lab tests relevancy for mitigation measures characterization.

Within Work package 3, different mitigation measures in track were tested, for several track configurations such as straight ballasted track, curve, turnout and slab track. All these measures are based on the modification of the track compliance (and therefore the wheel-rail interaction force) and the track transfer function (the response of the track to the vibration transmission). Their installations and tests in commercial track and/or scale 1 rig allow their efficiency to be appraised in realistic conditions of use.

WP4 - Mitigation measures on transmission / propagation

RIVAS Work package 4 focuses on vibration reduction technologies in the transmission path, either under or next to the track. In the frequency range of railway vibration, the top layer of soil plays an important role which is often neglected. It leads to a "cut-on frequency" above which a steep rise in the vibration transmission spectrum occurs. A key approach is therefore to take the layered ground structure into account or alter its effect to form barriers to propagation.

Options that were studied within the project include trenches, buried wall barriers, subgrade stiffening, horizontally layered wave-impeding blocks, and heavy masses at the soil surface. Open trenches and buried wall barriers will hinder the transmission of waves in the soil (Figure 11 - to be found in attached document). Similarly, heavy masses next to the track can block or reflect the ground-borne vibrations. Subgrade stiffening is often applied under railway tracks on soft soils to limit settlements or track displacements. It also reduces ground-borne vibration levels due to the increase in the effective stiffness of the soil beneath the track. The inclusion of wave impeding blocks under the track increases the cut-on frequency of the waves propagating in the top layer of soil. Because the layered ground structure plays an important role, all options are studied numerically for different ground types to establish the circumstances in which they are efficient.

To consolidate the results of the parametric study, three field tests were considered within the project: soil stiffening next to the track in alluvial conditions in Spain, a trench barrier in Switzerland, and a sheet piling wall as a wave barrier in Sweden.

Sheet piling wall in Sweden
The field test in Sweden is located in Furet in the southwest of Sweden along the West Coast Line between Gothenburg and Lund. A sheet piling wall designed and constructed by Trafikverket is subjected to a program of measurements and theoretical analysis within the framework of RIVAS.
Vibration problems at the site were reported to the Swedish Railway Administration. Indeed, the soft soil in Furet leads to high vibration levels in several buildings close to the track. The highest levels are measured in the frequency range of 4 - 5 Hz. A first attempt to mitigate vibration has been made in 2006. Under sleeper pads have been placed at the track closest to the buildings. At the same time the ballast of the other track has been exchanged and leveling of both tracks has been carried out. Unfortunately measurements performed after these measures showed insufficient vibration mitigation. Therefore it was decided to use a sheet piling wall as a method to further reduce the low frequency vibrations at the site.

Sheet piles are commonly used as retaining walls in geotechnical applications. Design calculations have indicated that sheet piles can also reduce ground-borne vibration. A sheet piling wall with a length of 100 m was installed next to the track behind the existing noise barrier in November 2011 (Figure 12 - to be found in attached document). The depth of the sheet piles is 12 m with every fourth pile extended to 18 m. These large depths are necessary to reduce the vibrations at very low frequencies (Figure 13 - to be found in attached document). Measurements after installation of the sheet pile wall have showed sufficient reduction of vibration levels in the exposed buildings, except for a small house with wooden structure at approximately 40 m distance from the track.

Comparison between measurement results for train passages before and after installation of the sheet pile wall indicate a significant reduction in vertical vibration levels at the soil surface behind the sheet pile wall. The effectiveness is higher doser to the wall where the maximum vibration levels are reduced by about 50 per cent. At 32 m the maximum levels are reduced by about 30 per cent while at 64 m from the track center, no reduction in maximum vibration levels is seen. It is also important to note that the construction of the sheet pile wall did not lead to an increase in vibration levels at the other side of the track.

The trends observed in the measurements are confirmed by theoretical analysis. Numerical simulations show that a sheet pile wall can act as an effective wave impeding barrier. The effectiveness of the wall however strongly depends on the characteristics of the soil. The design of a mitigation measure on the transmission path is therefore case specific and requires the knowledge of the soil layering and relevant soil parameters. Stiff buried wall barriers like the sheet pile wall will be more effective at sites with a relatively soft soil.

The results of the parametric study and the field tests are brought together in a design guide identifying a set of guidelines on the possible effectiveness of the mitigation measures in different soil types. The guidelines contain information on engineering design constraints, practicability, costs and social issues to form a technology assessment of the different mitigation methods on the transmission path.

WP5 - Mitigation measures on vehicles

The fifth and final technical work package within RIVAS was dedicated to the influence of rolling stock on ground-borne vibration. More specifically it investigated how properties of vehicle design, such as unsprung mass, suspension stiffness and axle spacing contributed to the excitation of ground-borne vibration. Furthermore work package 5 has been aimed at understanding the excitation of vibration caused by out-of-round wheels and to quantify this effect in relation to other excitation mechanisms related to the track.

Based on numerical models of vehicle, track and ground, parametric studies have been performed to assess the influence of an alternative vehicle design on the ground-borne vibration; not only for one specific case but considering a wide variation of ground conditions. In general, it is concluded that the influences of the carbody mass and the bogie mass are small on vibration that propagates to larger distances from the track. The secondary suspension comes into play at very low frequencies where other mechanisms related to the soil are often dominant. The primary suspension stiffness and in particular the unsprung mass are the two vehicle parameters showing the most significant influence on the vibration level. A modification of the primary suspension stiffness leads to a shift of some of the vehicle resonances and is hence a narrow-band
effect which is sensitive to variations in ground conditions. The potential of lowering the vibration level by reducing the
unsprung mass is however a broad-band effect which is less sensitive to particular ground conditions and hence has proven to
be most promising.

Focus - key results
Simulations of ground-borne vibration excited by freight and passenger trains have identified the unsprung mass (dominated
by the wheelset mass) to be the single most important parameter of the vehicle design. While the total mass (static axle load)
of the vehicle primarily influences the quasi-static excitation of vibration in the vicinity of the track, the unsprung mass has a
strong influence on the dynamic part of the excitation which gives rise to vibration that propagate away from the track. The
origin of the dynamic excitation is found in the wheel and rail irregularities which to some extent are present on all wheels and
rails. New wheels featuring low levels of out-of-roundness when leaving production may, during operation, develop into wheels
with severe out-of-roundness caused by non-homogeneous wear, plastic deformation and rolling contact fatigue cracking.

Figure 14 (to be found in attached document) shows three types of wheel out-of-roundness observed on a test train used
within the RIVAS project. These are the first three orders of out-of-roundness which may excite high levels of ground-borne vibration.

Measurement campaigns within RIVAS have shown that the expected positive effect by e.g. a low unsprung mass is difficult to
identify when studying vehicles with wheels in different conditions. The wheel irregularities mask the effect of other
parameters confirming the importance of considering the influence of the wheel condition. In order to assess the effectiveness
of a reduced out-of-roundness and a lower unsprung mass, simulations have been performed with different levels of track
irregularities, out-of-round wheels and unsprung mass. Input data for the simulations were prepared by studying
measurements of out-of-roundness for different types of wheels. The results show that the out-of-roundness of a wheel in
average condition may add up to 3 dB to the overall vibration level while an increase of up to 5 dB is seen in a single
frequency band. For a wheel in poor condition the increase is about 5 dB on the overall level and up to 15 dB in a single
frequency band.

Figure 15 (to be found in attached document) shows one example of the simulation results. Four different vehicle designs are
studied in combination with having wheels in good and poor condition. The results show that the reduction of the unsprung mass by 50
per cent leads to a broad-band reduction of 6 dB. Furthermore it can be seen that the potential reductions due to
low unsprung mass and wheels in good conditions are in the same order of magnitude. The improvement achieved by vehicle
design changes may therefore be completely lost if the level of out-of-roundness is not kept sufficiently low. Since the size of
the unsprung mass is closely related to the vehicle and drive concept, which is governed by requirements of comfort, safety
and reliability apart from requirement on ground-borne vibration emissions, a 50 per cent reduction of unsprung mass should
be considered as a large reduction difficult to achieve in practice. In order to reduce the ground-borne vibration levels, the
design of new vehicles should aim at lowering the unsprung mass. This must however not compromise the wheel resistance
against wear and the development of out-of-roundness. Vehicles already in service need to be maintained in order to avoid
high levels of out-of-roundness, and it is necessary to gain a better understanding of the mechanisms causing out-of-
roundness.

The work carried out within RIVAS Work package 5 has resulted in a good understanding of the vehicle influence on ground-
borne vibration. A reduction in vibration level can be achieved by lowering the vehicle unsprung mass of new vehicles.
However the first action to take in order to reduce the excitation of vibration already today is to improve wheel maintenance
and to prevent the growth of wheel out-of-roundness.

Potential Impact:
Conclusion
Within the frame of the EU FP7 project "Railway induced vibration abatement solutions (RIVAS)", a holistic approach to ground borne vibration due to railway traffic was adopted, with the aim of reducing annoyance of lineside residents. Mitigation measures studied apply to rail vehicle design, rolling stock maintenance, track design, track maintenance, subgrade engineering, and the transmission path within the railway infrastructure. Numerical modeling, allowing for elaborate parametric studies, was supported by field tests for verification and validation of predicted vibration reduction.

Results from the project have clearly shown that the effectiveness of vibration mitigation measures are highly depending on the type of train and train speed, the type of track, the soil conditions and even the type of buildings next to the track. These characteristics therefore need to be taken into account when selecting an appropriate vibration mitigation measure. In the final phase of the project, focus of the work goes to the writing of practical design guides, in order to facilitate implementation of vibration mitigation methods studied within the frame of the project.

The design guides, as well as all other public deliverables were made available on the project's website www.rivas-project.eu by the end of the year 2013 when the project came to a conclusion.

All dissemination activities of the RIVAS partners can be found under point 4.2 "Use and dissemination of foreground" Section A and Section B.

List of Websites:
www.rivas-project.eu

All relevant contact details can be found under above mentioned project website.