

1.2. MAIN S & T RESULTS

The main deliverables of the project are mitigation performance data sheets for vibrations from freight trains, including the new developed mitigation measures, a protocol for the assessment of mitigation measures and a guideline for the evaluation of human impact.

This chapter gives a description of these main results using the following headers:

- A guideline for the evaluation of human impact
- A protocol for the assessment of mitigation measures
- Mitigation performance data sheets for vibrations from freight trains
- New developed mitigation measures related to rolling stock maintenance
- New developed mitigation measures for the track infrastructure
- New developed mitigation measures in the propagation path

1.2.1. A guideline for the evaluation of human impact

The overall objective of the CargoVibes project was to develop and assess measures to ensure acceptable levels of vibration for residents living in the vicinity of freight railway lines in order to facilitate the extension of freight traffic on rail. Existing evaluation criteria in use are not properly underpinned by scientific data and there are no uniform assessment methods available to compare exposure from various studies.

AIMS

The overall aim for the specific work package pertaining to human response was to establish acceptable levels of vibration from railway transportation, and was subdivided with the following objectives:

Objective 1: To describe and assess reported health impacts of vibration among residents living near railway lines.

Objective 2: Experimentally evaluate sleep disturbance due to whole body vibration from railway transportation.

Objective 3: Provide a guidance document on how to apply the results in practice.

The main responsibility for Objective 1 was with TNO, Objective 2 with the University of Gothenburg (UGOT) and Objective 3 with the University of Salford (USAL). Shared initial work involved the development of questionnaire for the field study and the laboratory study, and later also the input given to the guidance document.

Objective 1

Objective 1 is fully reported in deliverable D1.2: Exposure-response relationships and factors influencing these relationships. A state of the art overview was given of the results from various field studies done so

far on the evaluation of vibration from several railway sources. On the basis of experience gained from these studies and from many previous studies on effects of noise on humans, a questionnaire was developed to measure self-reported response to vibration and noise, such as perception, annoyance and sleep disturbance. The process was carried out by a series of meetings, used previously in noise research, while also addressing specific issues related to vibration, for example the exact formulation of the vibration disturbance question and of attitudinal questions related to vibration. Furthermore, a set of questions on sleep quality was included to obtain comparable data for some parameters in the field as in the laboratory (see Objective 2). This questionnaire was translated from English into Dutch and Polish and checked by several native speakers. It was used in field surveys in the vicinity of a railway line with freight traffic in the Netherlands (N=156) and in Poland (N=104) to assess the response to (measured) vibration in combination with other individual and situational factors. Next, these survey data were combined with the original data from available earlier railway vibration field studies, providing complementary data for exposure-response analysis. To enable the comparison of the various metrics used in the separate studies, a conversion matrix was developed that allows the conversion of one metric into another. Subsequently, in a comparative meta-analysis, the expected degree of annoyance due to railway vibrations at a given vibration level was quantified in exposure-response relationships (Equations (1) to (12)).

Objective 2

Objective 2 is fully reported in deliverable D1.4: Results of the sleep disturbance study. To investigate sleep disturbance experimental studies were designed using vibration signals representative of the spectral content and amplitude of freight trains, based on field measurements provided by TNO, UGOT and USAL. Based on the field measurements and the technical range of the laboratory system we used a 10 Hz signal at three amplitudes ranging from a maximal weighted (W_d) amplitude of 0.0058 m/s^2 to 0.0204 m/s^2 . Horizontal vibration was rated as subjectively more annoying in a pilot study and so was used in the main trials (Smith et al. 2012). Different numbers of passages and interactions between noise and vibration exposure were examined. Across three studies a total of 59 young healthy volunteers participated. Gender and sensitivity to noise was balanced within the design. Physiological changes in cardiac activity and sleep macro- and micro- structure were recorded polysomnographically, and subjective ratings were collected in the morning and evening using questionnaires (Persson Waye et al. 2014, Smith et al. 2014).

Objective 3

Objective 3 is fully reported in deliverable D1.5: Guidance document for the evaluation of railway vibration. Guidance on how to apply the results of this work package in practice was developed in the form of a best practice guidance document. The objective of this deliverable was to provide guidance on the evaluation of human response to vibration from railways in residential environments. The deliverable outlines the currently available methods for the evaluation of disturbance from railway-induced vibration in residential environments. In addition, the deliverable presents the current state of the art in the human response to whole body vibration in the ranges of frequency and amplitude relevant to railway-induced vibration.

On 14th May 2013, a workshop was held at USAL that gathered international experts in the field of railway vibration from industry, consultancy, and academia. The aim of this workshop was to discuss key aspects

and challenges of the evaluation of vibration in residential environments with respect to human response. The outcomes of this workshop were used to shape and inform the contents of the guide. Additionally, a draft of the document was presented at the 11th International Workshop on Railway Noise in Uddevalla, Sweden and made available online for comment prior to it being finalized. These activities were undertaken to ensure the guidance document is relevant to the needs of operators, infrastructure managers, planners, consultants, scientists, and policy makers.

MAIN OUTCOMES

Objective 1

The surveys in the Netherlands and in Poland revealed influences of vibration and several individual and situational factors on annoyance and sleep disturbance. The survey data were combined with the original data from available earlier railway vibration field studies. In a comparative meta-analysis, the expected degree of annoyance due to railway vibrations was quantified for three different metrics in exposure-response relationships (Table 1 to Table 3 show the polynomial approximations of the underlying exposure-response model). Despite differentiation in the annoyance response between studies, there is a clear relationship between vibration exposure and the annoyance response of residents, which can be used as a basis of criteria for the evaluation of railway vibration (see also (Janssen et al. 2013)).

Table 1 Polynomial equations for proportion of respondents being slightly annoyed (SA), annoyed (A) and highly annoyed (HA) by vibration (directionally weighted maximum velocity $V_{dir,max}$, as used in DIN/SBR but directional). These equations must not be used outside the range 0.01 to 10 mm/s $V_{dir,max}$.

$\% SA_{V_{dir,max}} = -0.559X^4 - 2.594X^3 + 4.681X^2 + 31.802X + 36.118$	(1)
$\% A_{V_{dir,max}} = -0.863X^4 - 0.811X^3 + 8.602X^2 + 23.181X + 18.527$	(2)
$\% HA_{V_{dir,max}} = -0.460X^4 + 0.850X^3 + 7.620X^2 + 12.720X + 7.522$	(3)
$\text{where } X = \frac{\log_{10}(V_{dir,max}) + 0.5}{0.86733}$	

Table 2 Polynomial equations for proportion of respondents being slightly annoyed (SA), annoyed (A) and highly annoyed (HA) by vibration (weighted root mean square acceleration rms, as used in ISO). These equations must not be used outside the range 0.001×10^{-3} to 10×10^{-3} m/s² rms.

$\% SA_{rms} = -1.806X^4 - 3.198X^3 + 11.812X^2 + 35.059X + 25.390$	(5)
$\% A_{rms} = -1.648X^4 - 0.013X^3 + 13.826X^2 + 22.510X + 11.380$	(6)
$\% HA_{rms} = -0.527X^4 + 2.089X^3 + 9.850X^2 + 10.785X + 3.910$	(7)
$\text{where } X = \frac{\log_{10}(rms) + 4}{1.1564}$	

Table 3 Polynomial equations for proportion of respondents being slightly annoyed (SA), annoyed (A) and highly annoyed (HA) by vibration (weighted vibration dose value VDV, as used in BS). These equations must not be used outside the range 0.1×10^{-3} to 1000×10^{-3} m/s^{1.75} VDV.

$$\%SA_{VDV} = -1.751X^4 - 4.019X^3 + 10.845X^2 + 38.038X + 29.118 \quad (9)$$

$$\%A_{VDV} = -1.952X^4 - 0.768X^3 + 14.679X^2 + 26.054X + 13.832 \quad (10)$$

$$\%HA_{VDV} = -0.885X^4 + 1.834X^3 + 11.605X^2 + 13.529X + 5.086 \quad (11)$$

$$\text{where } X = \frac{\log_{10}(VDV) + 2}{1.1564} \quad (12)$$

Objective 2

From the experimental studies it can be concluded that nocturnal vibration may have a negative impact on sleep, and that the effect increases with greater vibration levels. Both noise only and noise accompanied by low vibration had little effect, while noise and high vibration level was found to significantly influence both subjective evaluated sleep (Figure 2) and physiological measures of sleep (Figure 1). At the levels used, vibration only and noise only both contributed towards physiological reactions, and their combined effects appeared directly additive on the probability of sleep stage changes and cortical arousals. The effect of number of trains was less conclusive and requires additional research.

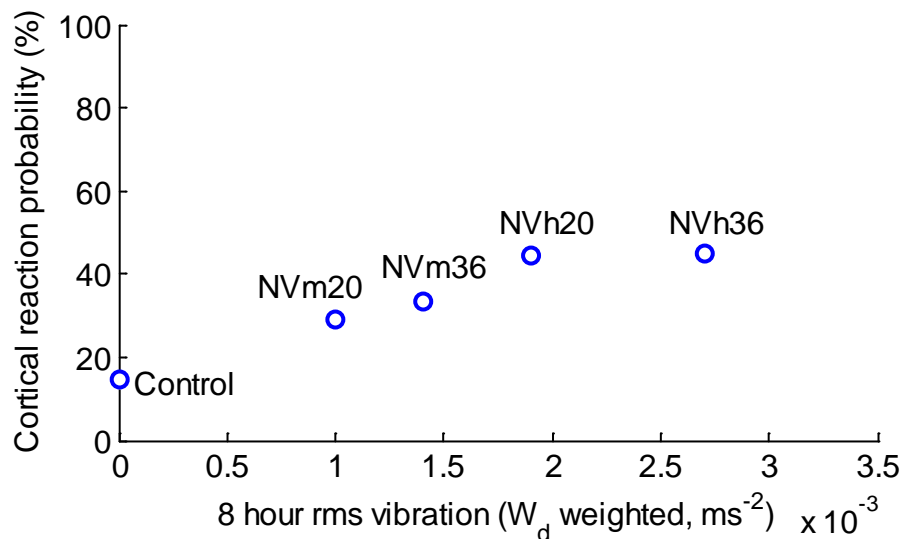


Figure 2 Event-related cortical reaction probability (EEG arousals and awakenings) to freight trains in the UGOT laboratory study II. Nights with noise and moderate (m) or high (h) vibration and 20 or 36 trains.

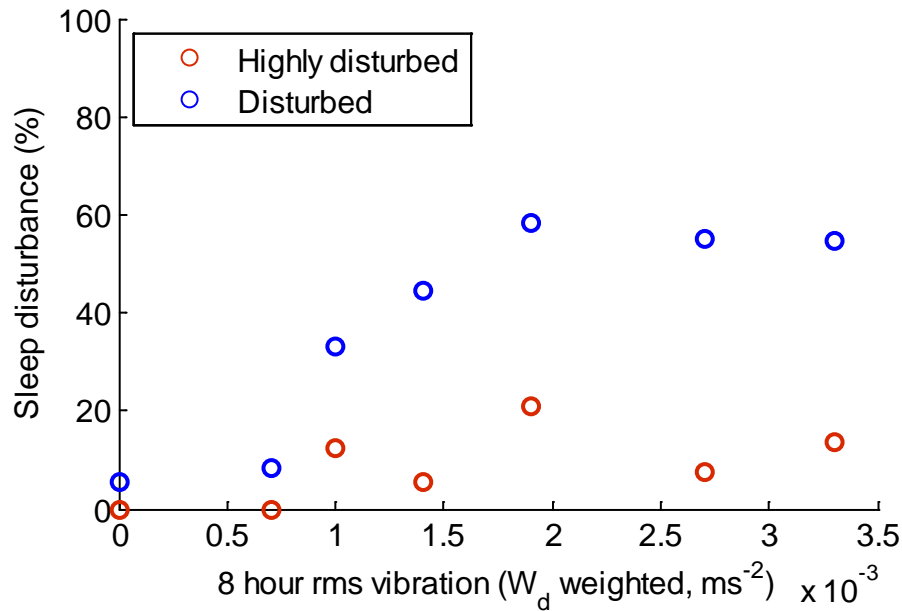


Figure 3 Sleep disturbance by vibration in the UGOT laboratory studies

Objective 3

A guidance document was produced, derived from the main conclusions of the work package and other published literature, describing how to apply the results in practice (Woodcock et al. 2014). This represents a significant first step towards harmonization of methods in the assessment of human response to railway vibration. It provides a set of practical tools to assess railway induced environmental vibration including a summary of current national standards, polynomial fits to the exposure-response curves, proportions of people annoyed at current guidelines as predicted by the meta-analytic curves (Table 1 to Table 3), information on the significant effects of vibration on sleep, and the influence of non-exposure factors (Table 4). The document is intended to provide an extension to the currently available body of guidance in light of the current state of the art, allowing assessments of vibration to be conducted based on the most up to date scientific information.

Table 4 Summary of the effects of non-exposure factors on annoyance

Factor		Significant findings
Time of day	Evening	Annoyance greater during the evening than during the day at the same level of vibration exposure
	Night	Annoyance greater during the night than during the evening at the same level of vibration exposure
Situational	Visibility of source	Annoyance greater if the source is visible
	Time spent at home	Annoyance greater for people who spend fewer than 10 hours per day at home
	Type of area	Annoyance greater for people living in rural areas
Attitudinal	Concern of damage	Annoyance greater for those concerned that vibration is damaging their property of belongings

Expectation regarding future vibration	Annoyance greater for those expecting vibration to get worse in the future
Necessity of source	Annoyance greater for those considering the source unnecessary*
Noise sensitivity	Annoyance from vibration greater for those considering themselves as noise sensitive
Socio-demographic Age	Annoyance greater for those in the middle age group

*This result was observed for freight trains and may not be generalizable to mixed railway

Concluding comment

The outcomes of this workpackage represent a significant advance in the understanding of annoyance and sleep disturbance to railway vibration and a step towards a much needed harmonization of assessment methods. The findings highlight the importance of considering environmental vibration in the planning, construction, and maintenance of railways in residential environments.

1.2.2. A protocol for the assessment of mitigation measures

A general measurement protocol is presented to assess the efficiency of a vibration mitigation system, with three different methods.

The following conclusions and remarks are made concerning the first general direct evaluation method, which is applicable for all types of mitigation measures:

1. The first method consists of a direct comparison of measurements in the same target point(s) “before” and “after” the implementation of the mitigation measure. Thus, the reduction factor in target points at the distance from the track is directly calculated when the measured vibration amplitude at these target point is available for the reference case (before the installation of the mitigation measure) as well as for the situation after the installation of the mitigation measure, all other conditions remaining unchanged. The reference case can eventually be measured simultaneously with the situation after installation of the mitigation measure at a different location where no mitigation measure is present, but where all other conditions are identical (train type, train speed, distance from track, soil characteristics, wheel and track characteristics which are not part of the mitigation measure to be evaluated, ...).
2. It is an essential requirement that the train conditions ‘after’ remain unchanged compared to ‘before’ the introduction of the mitigation measure. However, in practice, even in a particular part of the railway network, the speed, the wheel condition and the loads of the trains change from one passage to another, which often results in a noticeable variation in the excitation force. This variation can be quantified by means of control measurement points far enough from the location of the system not to be influenced by the mitigation measure. The difference between the measured signals at the control point locations before and after the introduction of the mitigation measure can be used to correct the measurements made in the target points after the introduction of the mitigation measure. This correction is of course not to be carried out if the mitigation measure consists in a modification of the wheel surface, wheel geometrical characteristics or other vehicle characteristic (e.g. suspension). It is proposed to use two control locations:

one close to the track where the measured vibrations can be considered coming from a point source and one further from the track where the measured vibrations can be considered coming from a line source.

Practically, because of the site limitations, the test configuration may not include the possibility for control points. In that case, an average of measured vibrations before and after the introduction of the mitigation measure should be considered. This average must be applied over similar train passages. The similarity between the passages is determined by different parameters such as the type of trains (local passenger, freight, and high-speed), axle loads, the speed, and the length of the trains. In case of passage of freight trains it might be difficult to find similar passages. This is why, in such conditions, certain parameters, such as the number of averages, is not to be defined and should be determined using best engineering judgement.

3. The ground vibrations from several train passages are recorded by accelerometers that are located in receiver positions along a line or in an area. The shadow zone denotes the area behind the isolating system that is protected from the incoming waves generated by the source. This protection results in a reduction of the vibration amplitudes.

The receivers behind the isolating system are generally located in target locations (which define a target area) which are the locations where the vibration criteria have to be evaluated. These points can be on the soil just before the foundation of a building, on the foundation itself, inside the buildings or on the soil at locations where future buildings are to be constructed. The target locations should at least include those points in which vibration assessment has to be made according to the guidelines or standards which are used in the specific project (DIN, ISO, BS, FTA,...). For some mitigation measure types, the insertion loss is function of the distance between the track and the target location.

It is recommended to measure the acceleration at the above defined locations in the three directions (vertical, perpendicular to the track and longitudinal), especially when dealing with freight train ground vibrations. For the type of measurement equipment, the type of data processing and reporting we refer to ISO 14 837-1. The data analyses should at least include the processing (in terms of filtering, evaluation parameters, frequency band, ...) as defined in the guidelines or standards which are used for the specific project.

It is recommended to add some additional measurement locations along a centreline situated between the tracks and the target areas. This allows for verification of the validity of the models used in the design of the mitigation measures. The exact location of these additional measurement locations (points) is to be made using best engineering judgement since local site conditions and relative location of tracks, vibration mitigation measure and receiver (target location) prevent to make generally valid proposals for the location of those additional points.

Two other methods can be used to evaluate the efficiency of an isolating soil barrier, when the ground vibrations before the barrier installation are unknown. These two methods are illustrated with a numerical example based on the two-dimensional numerical modelling of the problem. The second method works very well in the case where the soil conditions are symmetric with respect to the track. The third method is a semi-analytical method based on ground vibrations just before and just after the soil barrier, during train passage. For this purpose, the analytical equation for an isolating barrier system is developed using the one-dimensional shear wave propagation. The results of the third method correspond very well with those obtained by the direct method also at low frequencies where mitigation against freight train

vibrations must be evaluated. The third method is innovative and will require further research, adaptation and validation in order to become a generally accepted method.

The applicability of the proposed methods is demonstrated using a full-scale test of an isolating barrier and of wave impeding blocks along an existing railway line.

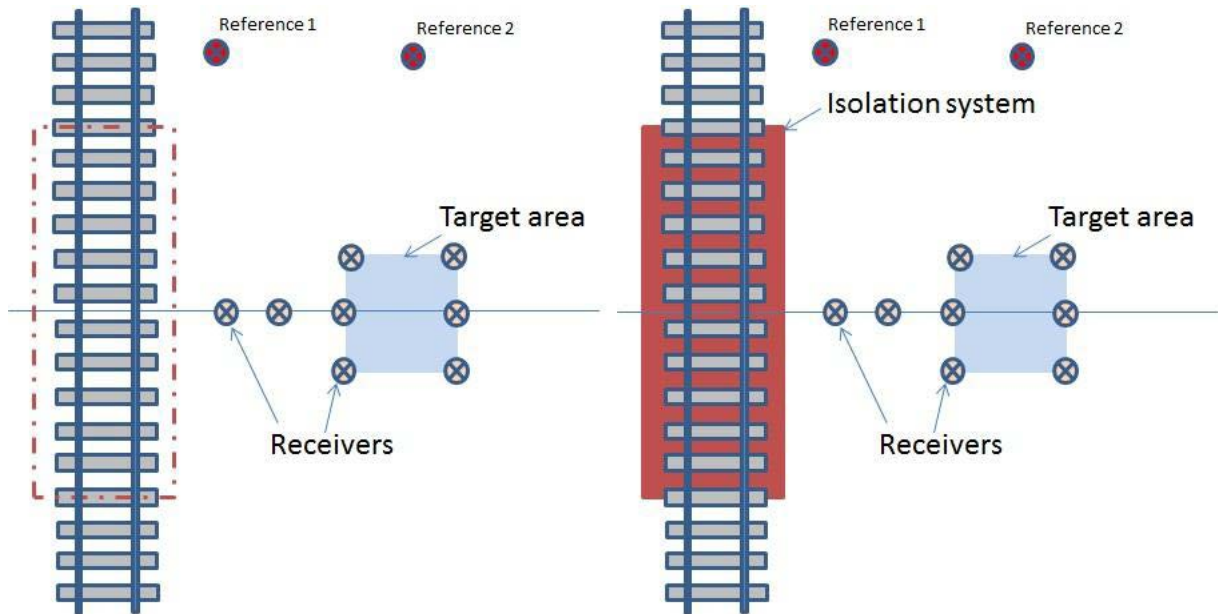


fig. 4: before-after measurement for track based measures, using reference points

3. The ground vibrations from several train passages are recorded by accelerometers that are located in receiver positions along a line or in an area. The shadow zone denotes the area behind the isolating system that is protected from the incoming waves generated by the source. This protection results in a reduction of the vibration amplitudes.

The receivers behind the isolating system are generally located in target locations (which define a target area) which are the locations where the vibration criteria have to be evaluated. These points can be on the soil just before the foundation of a building, on the foundation itself, inside the buildings or on the soil at locations where future buildings are to be constructed. The target locations should at least include those points in which vibration assessment has to be made according to the guidelines or standards which are used in the specific project (DIN, ISO, BS, FTA,...). For some mitigation measure types, the insertion loss is function of the distance between the track and the target location.

It is recommended to measure the acceleration at the above defined locations in the three directions (vertical, perpendicular to the track and longitudinal), especially when dealing with freight train ground vibrations. For the type of measurement equipment, the type of data processing and reporting we refer to ISO 14 837-1. The data analyses should at least include the processing (in terms of filtering, evaluation parameters, frequency band, ...) as defined in the guidelines or standards which are used for the specific project.

It is recommended to add some additional measurement locations along a centreline situated between the tracks and the target areas. This allows for verification of the validity of the models used in the design of the mitigation measures. The exact location of these additional measurement locations (points) is to be made using best engineering judgement since local site conditions and relative location of tracks,

vibration mitigation measure and receiver (target location) prevent to make generally valid proposals for the location of those additional points.

Two other methods can be used to evaluate the efficiency of an isolating soil barrier, when the ground vibrations before the barrier installation are unknown. These two methods are illustrated with a numerical example based on the two-dimensional numerical modelling of the problem. The second method works very well in the case where the soil conditions are symmetric with respect to the track. The third method is a semi-analytical method based on ground vibrations just before and just after the soil barrier, during train passage. For this purpose, the analytical equation for an isolating barrier system is developed using the one-dimensional shear wave propagation. The results of the third method correspond very well with those obtained by the direct method also at low frequencies where mitigation against freight train vibrations must be evaluated. The third method is innovative and will require further research, adaptation and validation in order to become a generally accepted method.

The applicability of the proposed methods is demonstrated using a full-scale test of an isolating barrier and of wave impeding blocks along an existing railway line.

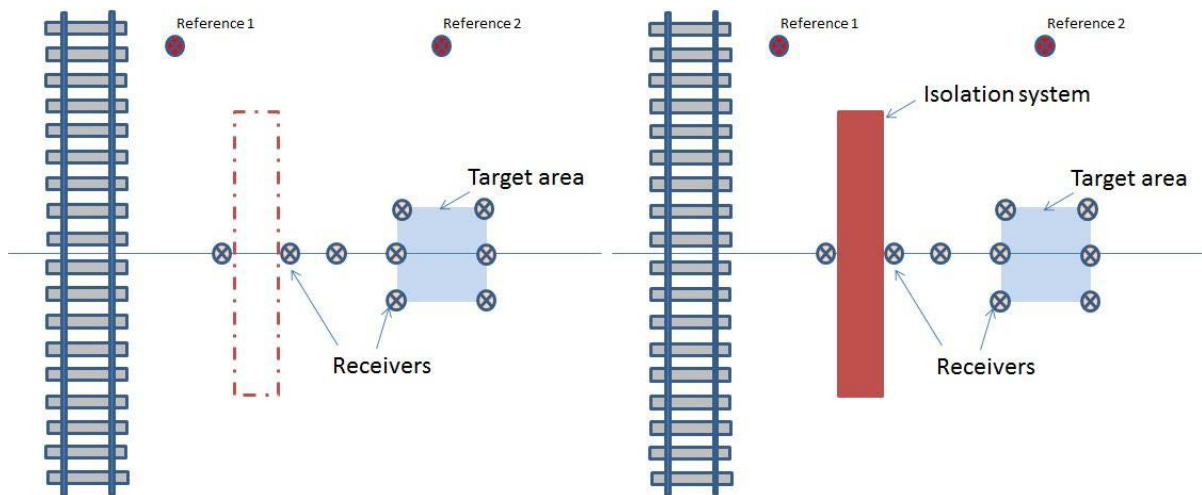


fig. 5: before-after measurement for measures in the propagation path, using reference points

1.2.3. Mitigation performance data sheets for vibrations from freight trains

In order to cope with a vibration problem in the lower frequency range (below 20 Hz), which is more probable with freight trains than with passenger trains, in view of the much higher vibration intensity of freight trains in the lower frequency range, solutions have been proposed in D2.6. Following cost related remarks are to be made concerning these solutions.

Maintenance

Maintenance procedures that are particularly effective at reducing the low frequency freight train ground-borne vibrations include:

- Rail grinding on a regular basis, particularly for low speed freight trains.
- Wheel truing to re-contour the wheel, remove wheel flats.
- Reconditioning vehicles, particularly use brake types which do not generate wheel flats
- Ballast tamping and track re-alignment are of particular importance for freight trains.

LCC and CBA issues and info:

- Rail grinding is only of interest to reduce the vibrations of low speed freight trains. Reducing the combined effective roughness (wheel and rail) by a factor of 2 reduces the vibration levels by a factor of 2 (6 dB). Using rail grinding as vibration mitigation measure will require the establishment of the max. acceptable rail roughness level (corresponding with a vibration limit in the target area- building), the monitoring of the rail roughness in the sensitive area and a grinding operation as soon as the rail roughness limit has been reached. Regular rail grinding can be beneficial for the complete life cycle cost of the track: it can result in a longer life time of the rail as long as the grinding operations (material removals) are not too frequent. The global cost picture does depend on the number of vibration guided grinding operations which will be function of many parameters: max. rail roughness limit, rail roughness growth rate,... A more detailed analysis of the economics of rail grinding is given in chapter 3.
- Tamping (improving track geometry for wavelengths of 1 - 36 m) is a good mitigation measure to reduce the low frequency vibrations from freight trains at conventional speeds. Reducing the effective track geometry deviation by a factor of 2 reduces the vibration levels by a factor of 2 (6 dB). Using tamping as vibration mitigation measure will require the establishment of the max. acceptable track geometry deviation (corresponding with a vibration limit in the target area- building), the monitoring of the track geometry in the sensitive area and a tamping operation as soon the track geometry deviation limit has been reached. Too frequent tamping can reduce the life time of the ballast bed from e.g. 40 years to 25 years. The global cost picture does depend on the number of vibration guided tamping operations which will be function of many parameters: max. track geometry deviation limit, track geometry deviation growth rate,... A more detailed analysis of the economics of track tamping is given in chapter 3.
- Use of K brake blocks (or LL brake blocs) will reduce the generation of wheel flats and wheel roughness drastically. A reduction of ground borne vibrations of min. 6 dB is anticipated. It is very important to mention that this solution is also very effective airborne noise abatement solution (reduction of 8-10 dB(A)). This is well explained, together with detailed cost information in the following UIC document: Railway noise in Europe, A 2010 report in the state of the art, published by

the International Union of Railways (UIC) 16 rue Jean Rey - F-75015 PARIS, first edition September 2010, authors: Jakob Oertli and Peter Huebner.

- Wheel truing is a good mitigation measure to reduce the vibrations from freight trains. Removing all wheel flats can reduce the vibration levels by 10 dB. This is discussed in deliverable D3.1 Using wheel truing as vibration mitigation measure will require the monitoring of wheel flats and their location (axle and vehicle), and a truing operation as soon as wheel flats have been detected.

Location and Design of Special Trackwork

In WP3 and WP4 measures were designed and validated to reduce the vibration increase at turnout locations, making use of very high resilient pre-compressed rail fastener in the frog (point) area.

It is too soon to give data on the proposed solution: the solution is local, limited to a number of sleepers, its cost is non-negligible, it might need maintenance and its lifetime has to be assessed. It is anticipated that more robust sustainable designs will be developed after the concept has been proof tested.

Special Track Support Systems

The control measures considered for track support with low frequency vibration mitigation potential are discussed below:

- Very resilient Fasteners: Very resilient pre-compressed rail fasteners mounted on concrete sleepers will be designed and validated for use in curves, in order to reduce rail roughness growth and rail corrugation. Their potential for mitigating low frequency soil vibrations from freight trains will be reported in WP4 deliverables. Concerning LCC and CBA it is too soon to give data on the proposed solution: the solution is limited to all sleepers in the sensitive area, its cost is non-negligible, it might need maintenance and its life time has to be assessed. It is anticipated that more robust sustainable designs will be developed after the concept has been proof tested.
- Under sleeper pads: a resiliently supported sleeper system consists of sleepers supported by elastomer pads. The rails are fastened directly to the sleepers using standard rail clips. The vibration control effect in the low frequency range of this track support system depends on its ability to maintain a very good track geometry in function of passing tonnage and time. The pad stiffness required might be in conflict with the pad stiffness required for high frequency mitigation. This solution will be tested in the Infrabel network and reported in WP4 deliverables. Some cost information will be given in chapter 3. It is anticipated that life time of the track and ballast can be prolonged with this solution.
- Ladder Track: Cargovibes simulations have shown that the ladder track design itself does not result in reduced vibration emission in comparison with standard ballasted track with concrete sleepers. The vibration control effect in the low frequency range of this track support system depends on its ability to maintain a very good track geometry in function of passing tonnage and time. Test conducted at TTCl (Pueblo,US) indicate that the requirement for ballast tamping is reduced very significantly with ladder track. This solution comes at a high cost and the initial installation requires skilled specialised contractors. This solution might have potential in the future after further development. Extensive CBA and LCC data for existing designs is given in chapter 3.
- Larger sleepers: As the ladder track, the vibration control effect in the low frequency range of this track support system depends on its ability to maintain a very good track geometry in function of

passing tonnage and time. Test conducted at TTCI (Pueblo) indicate that this is a valuable alternative to the ladder track in terms of reducing tamping and maintaining a good track geometry. It comes at a smaller cost than ladder track. This solution, in combination with under sleeper pads, will be tested in the Infrabel network and reported in WP4 deliverables. Some cost information will be given in chapter 3. It is anticipated that life time of the track and ballast can be prolonged with this solution.

Soil barriers

A soil barrier will be an effective freight train vibration barrier if it changes the propagation characteristics of the soil in the low frequency region. This solution will yield a 5-10 dB reduction in low frequency vibration levels when properly designed and in a specific area behind the barrier. This solution does not affect the railway system. It comes at an investment cost without anticipated maintenance. LCC and CBA info on this solution is given in chapter 3. It is important to note that this solution might lead to increased land value for the shadow zone behind the barrier system (outside the scope of our evaluations).

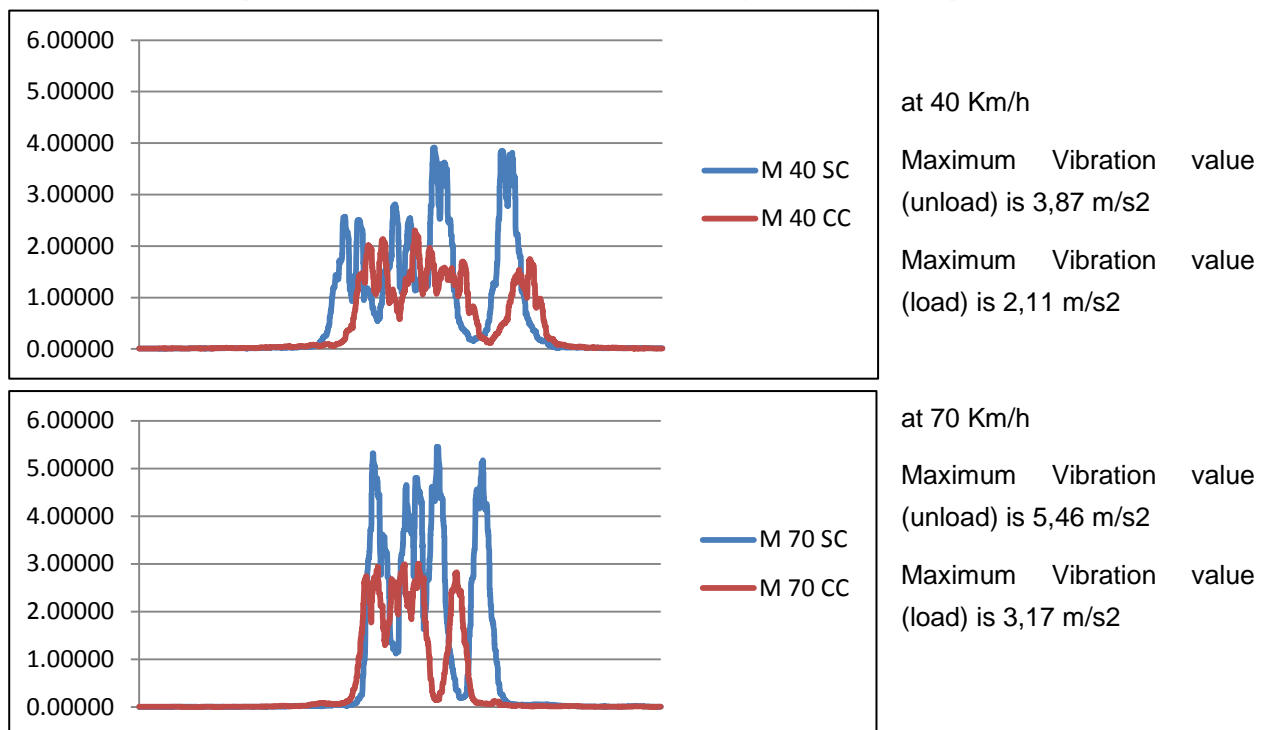
1.2.4. New developed mitigation measures related to rolling stock maintenance

In order to understand and characterize the mitigating measures of vibrations in freight trains, it is important to know quantitatively what is expected to obtain as vibration value at the origin, in different situations and compare the effects of various factors on the vibration result.

Some trials were performed, on a controlled environment in different tracks using a specific type rolling stock (locomotive and wagon). In particular, selected wheel defects that affect vibration and the vehicle speed were used as test parameter and varied within the allowable range, considered as the representative one.

Here, some of the parameters that have more influence in vibration intensity have been analysed. The plan was to perform trials in different tracks using a specific type rolling stock (locomotive and wagon).

Figure 6 Comparison between UNLOAD and LOAD wagons at different speeds



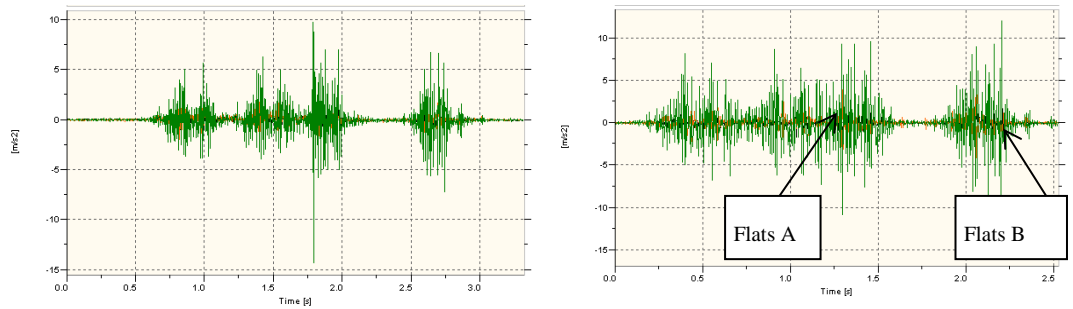
Conclusion

The results show that it is clear the influence of speed in unloaded wagons obtaining higher levels of vibration for higher speeds, increasing speed from 40 Km/h to 70 Km/h results in an increase of 2 m/s² in vibration in the vertical direction. This influence is not so clear for loaded wagons, where an increase in speed from 40 to 70 Km/h results in an increase in vibration of less than 1 ms².

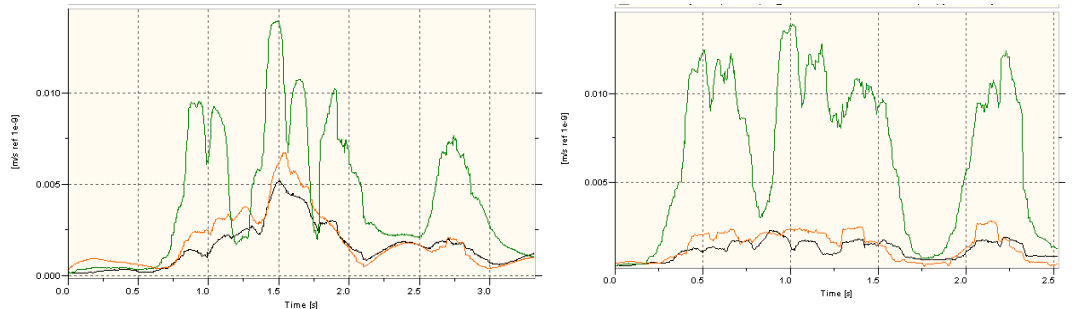
In addition, some wheel defects have been tested to evaluate their quantitative influence in vibration intensity.

Figure 7 Results with wheel defects - flats A – 60 mm flats B – 35 mm values for vertical (green) and horizontal (orange and black) propagations

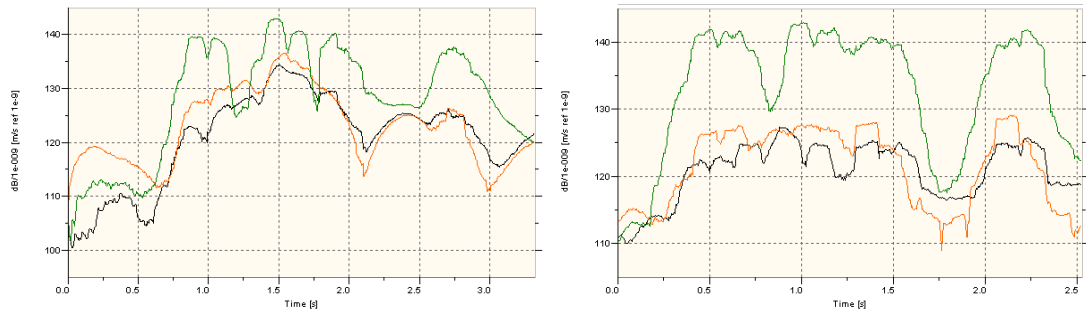
Wave form for passage of wagon with induced flats



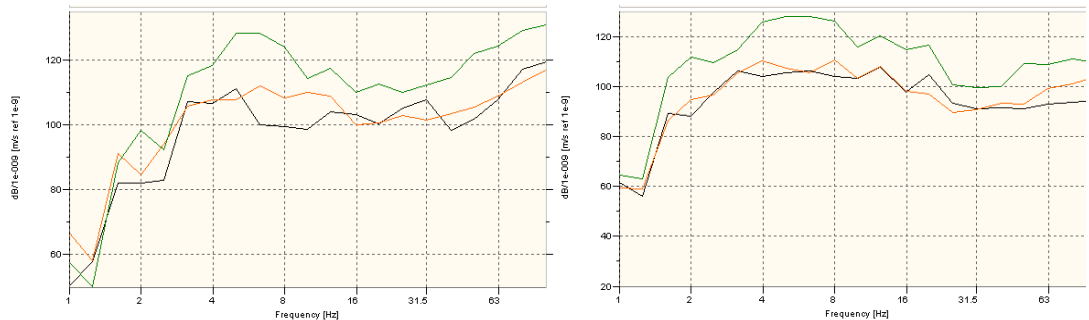
RMS value for passage m/s



RMS value for passage dB



spectrum



The occurrence of flats is one of the most common issues on wagon wheels and that really induce high vibrations at wheel/rail contact. The performed study shows the effect of the flat presence in a wheel can increase the maximum vibration level to very high values that clearly emerge from the vibration levels of the rest of the train. The measurements on the sleeper shown that the peak (at the wheel with the flat) can achieve 20 dB above the mean value (rms) of vibration from the whole train.

Maintenance Strategy Analysis

In the scope of the project it has been addressed an analysis which intends to evaluate the wheel maintenance strategy under the current program for wear and defect limits and how this strategy will be affected by changing the maintenance program in terms of tightening the intervention limits. This is achieved by suggesting a new maintenance cycle and new intervention limits. The cycle and intervention limits presented are just one of the several possibilities that can arise during an evaluation of this kind. The study was performed for the series of wagons which has been used in the previous trials.

Platform wagon Sgnss 12 94 455 2 001/300. This vehicle is composed of Y25 bogies with an average tare of 21.6 tonnes and 120 km/ of maximum speed. This type of wagon is used for containers and swap bodies transportation.

The maintenance cycle defines the wagon maintenance conditions which guarantee the appropriate conservation for a regular exploitation from the point of view of utilization and safety circulation. All the maintenance tasks are performed by skilled companies, namely for maintenance and repair of freight rolling stock.

The maintenance cycle defined for this serie of wagon is presented in the following table:

Table 5 Maintenance cycle

Description	VO	RS	RSP	RP
Wagon Cycle	12 month + 1 month	3 years + 3 months	6 years + 3 months	12 years + 3 months
Mandatory	Yes	By Sampling	Yes	Yes

VO – Operational Intervention; RS – Safety Intervention; RSP – Primary Safety Intervention; RP – Primary Overhauling

With the goal of having flexibility in the operations, a three months tolerance is established over the limit for RS, RSP and RP interventions and a month tolerance is defined over the limit for VO intervention. These tolerances are defined in the reference document “GCU – General Contract of Use for Wagons”. In the specific case of the *RS – Safety Intervention* the sampling is defined in the reference document “GCU – General Contract of Use for Wagons”.

In each of the interventions mentioned previously there are tasks that must be performed. Here, only the tasks related to the running gear, namely the wheelset, are presented. The interventions are composed by the tasks presented in table 6.

Table 6 Tasks included in the different interventions

Running Gear – Wheelset (f)	VO	RS	RSP / RP
General aspect observation	X	X	X
Restitution of wheelset life cycle			X (a)
Verification of distance between of wheels internal face		X	(b)
Observation of geometric profile and wheel thickness	X	X	(b)
Verification of geometric profile and wheel thickness (e)		X (c)	(b)
Verification of defects at wheel tread (e)	X	X	(b)
Verification of axle bents and cracks			(b)
Verification of wheelset axle journal (d)			X (d)

(a) – wheelset substitution due to wear should only occur when the wheel thickness limit is achieved

(b) – tasks included in the restitution of wheelset life cycle

(c) – depends of the observation status

(d) – always when wheels are changed

(e) – Defects like: flats, shelling, cavities, axial run-out, radial run-out. Geometric profile: flange width and height, monobloc thickness, qR

(f) – tasks performed manually, visually and automatically (includes measurements with UIC gages and other tools and NDT testing). If the limits for defects and geometric profile are achieved during observation and verification of geometric profile and defects at wheel tread, the wheels must be turned.

The tasks included in table 6 are based in standards that have limits for wheelset and wheel geometry and defects deviation. These limits are expressed in the ANNEX A – MAINTENANCE OF WHEEL AND WHEELSET GEOMETRY of the Deliverable 3.1 – Maintenance limits – Wheel & rails surface. Although they are already in the document mentioned before, these limits are presented again in the following tables:

Table 7 Operational limits for wheelset wear and defects

Parameter	Symbol	Maximum Vehicle Speed (km/h)			
		≤ 120	≤ 160	≤ 200	> 200
Maximum flange width	Sd max	33 mm			
Minimum flange width	Sd min	22 mm (for new wheels with $\varnothing > 800$ mm) / 27,5 mm (for new wheels with ≤ 800 mm)			
Thickness difference of flanges in the same wheelset	ΔSd	≤ 2 mm			
Maximum flange height	Sh max	36 mm			
Minimum qR	qR min	6,5 mm			
Distance between internal face of wheels	Di	1590 ≤ Di ≤ 1596			
Maximum axial run-out	E max	1,5 mm	1 mm		

Maximum radial run-out (ovalization)	O max	1,5 mm	1 mm	0,7 mm	0,5 mm
Diameter difference between wheels of different wheelsets	$\Delta\emptyset$	Depend on the vehicle: typical values 1 mm to 20 mm			
Flats and metal build up					
$\emptyset \geq 1000$ mm		≤ 80	≤ 60	≤ 50	≤ 35
$840 \text{ mm} \leq \emptyset \leq 1000$ mm		≤ 60	≤ 50	≤ 30	≤ 25
$630 \text{ mm} \leq \emptyset \leq 840$ mm		≤ 50	≤ 35	≤ 25	≤ 20
$330 \text{ mm} \leq \emptyset \leq 630$ mm		≤ 35	≤ 30	-	-

Table 5 – Wheel turning tolerances

Parameter	Symbol	Maximum Vehicle Speed (km/h)			
		≤ 120	≤ 160	≤ 200	> 200
Distance between internal face of wheels	D_i	$1590 \leq D_i \leq 1596$			
Axial run-out	E	≤ 1 mm	$\leq 0,8$ mm	$\leq 0,5$ mm	$\leq 0,3$ mm
Radial run-out (ovalization)	O	$\leq 0,5$ mm	$\leq 0,3$ mm		
Divergence in profile shape		$\leq 0,5$ mm			
Flange Inclination	qR	> 8 mm			
Flange height	Sh	Min. 28 mm for wheels with $760 \text{ mm} \leq \emptyset \leq 1000$ mm			
		Min. 30 mm for wheels with $630 \text{ mm} \leq \emptyset < 760$ mm			
		Min. 32 mm for wheels with $330 \text{ mm} \leq \emptyset < 630$ mm			
Flange thickness	Sd	$26 \text{ mm} \leq Sd \leq 32,5$ mm			
Diameter difference between wheels of same wheelset	$\Delta\emptyset$	$\leq 0,5$ mm		$\leq 0,3$ mm	
Roughness of profile surface	Ra	$\leq 12,5$ μm			

NOTE: cells in green represent the limits for the wagon Sgnss 12 94 455 2 001/300

Table 8 Suggested Maintenance Limits

Parameter	Symbol	Current Maintenance Limits	New Maintenance Limits
Maximum flange width	Sd max	33 mm	-
Minimum flange width	Sd min	22 mm (for new wheels with $\emptyset > 800$ mm) / 27,5 mm (for new wheels with ≤ 800 mm)	-
Thickness difference of flanges in the same	ΔSd	≤ 2 mm	-

wheelset			
Maximum flange height	Sh max	36 mm	-
Minimum qR	qR min	6,5 mm	-
Distance between internal face of wheels	Di	$1590 \leq Di \leq 1596$	-
Maximum axial run-out	E max	1,5 mm	1 mm
Maximum radial run-out (ovalization)	O max	1,5 mm	1 mm
Diameter difference between wheels of different wheelsets	$\Delta\emptyset$	Depend on the vehicle: typical values 1 mm to 20 mm	
Flats and metal build up			
$840 \text{ mm} \leq \emptyset \leq 1000 \text{ mm}$		$\leq 60 \text{ mm}$	$\leq 30 \text{ to } 48 \text{ mm}$

As it was presented in the current document, the interventions included in the maintenance cycle are based in fixed temporal intervals. The most frequent intervention is the VO – Operational Intervention which occurs each year. Being the average travelled annual distance of the specified wagon of 50.000 km, it means that the VO – Operational Intervention occurs approximately every 50.000 km.

In order to achieve the proposed modifications, interventions need to be more frequent and be based not only in fixed temporal intervals but also based in travelled distance (like passenger vehicles). In passenger vehicles, tasks related with wheels geometric verification and defect search occur more often. These tasks take place approximately every 25.000 km for geometric verification and every 10.000 km for defect search (this is different for each fleet of vehicles due to different commercial services). This is the suggestion for the new wagon maintenance cycle in terms of wheel maintenance. The VO, RS, RSP, RP interventions will not suffer any modification, only new interventions will come up before VO. In the following table the suggested cycle is presented:

Table 9 Suggested Maintenance Cycle

Description	DF	WSV	VO	RS	RSP	RP
Wagon Cycle	12.500 km	25.000 km	12 month + 1 month Approximately (50.000 km)	3 years + 3 months	6 years + 3 months	12 years + 3 months
Mandatory	Yes	Yes	Yes	By Sampling	Yes	Yes

Note: For practical reasons DF will be performed each 12.500 and not 10.000

DF – Defect Observation Intervention; WSV – Wheelset Verification

COSTS RELATED WITH WAGON MAINTENANCE

For the current maintenance program that was presented in the previously chapters there is a fixed cost that is paid by the freight operator to the maintenance manager. These costs include equipment depreciation and consumables, vehicle occupancy at workshop and all the necessary labour to perform the interventions. Here, only labour costs are analysed.

The different interventions need different labour (e.g.: VO – 8 hours; while RSP – 20 hours; RP – 40 hours). The new suggested interventions will take one hour for DF and two hours for WSV.

It is clear that the vehicle will be more times at the workshop for maintenance. Comparing with the current maintenance strategy the vehicle will be four times per year stopped for maintenance while for the current maintenance this would be only once. Although the necessary interventions (DF and WSV) will require less labour hours than VO, it is obvious that the overall labour hours will increase. For this specific case the amount of hours will have a 50 % increase.

CONCLUSION

Although this document does not identify the actual costs related to wagon maintenance, the goal of the document is achieved due to the conclusions that can arise from it. The costs vary from country to country and the most important issue is to quantify how much maintenance costs can increase to accomplish the new maintenance strategy. It is evident that in order to achieve the new maintenance program, which will lead to a better wheelset condition, the costs will increase. Depending on how the vibration/noise intensity affects the operation of freight vehicles, it is an option for the operator in applying this maintenance strategy

1.2.5. New developed mitigation measures for the track infrastructure

A study performed by several partners during the project concluded that the main benefit for the mitigation of vibrations at the track infrastructure, is to be found in the long-term track stability, especially from the viewpoint of (vertical) geometry. The better the track geometry is maintained over time, the lower the track degradation speed, and the smaller the generation of vibrations. Especially at "hot spots" such as switches and curves, this plays an important role.

The benefit of laddertrack seems to lay especially in this aspect, and not so much in the more uniform distribution of the dynamic loads (as initially thought). But as other, more current systems may lead to a similar increase in track stability / geometry over time, the laddertrack idea was abandoned halfway the project, refocusing on these more currently used systems, having the advantage of already being homologated in most EU track networks.



fig. 8: a typical laddertrack setup with ballast

The use of resilient elements, possibly in combination with specially shaped sleepers, can indeed lead to a more smooth contact between the track components, thereby increasing their longevity on the one hand, and to reduced friction effects inducing vibrations on the other hand. As the stiff track components (rail, sleeper,...) can now slightly move and rotate relative to each other, thanks to the soft elastic contacts, the track obtains a higher adaptability when trains are running over.

For curves, the following mitigation measures are considered:

- soft USP's (= "Under Sleeper Pads"), preferably with a wavy surface at the underside, to obtain a good grip with the underlying ballast stones, thereby improving the lateral stability of the curved track. The USP is laid down into the freshly poured concrete during production, using a special bonding layer in textile, that "hooks" into the concrete for a perfect adhesion of the USP.



fig. 9: a wavy USP glued onto a concrete sleeper (during production, so here positioned upside down)

- heavy H-shaped concrete sleepers, providing a very high stability over time, especially when combined with the above mentioned USP's; once installed, these sleepers remain very stable, significantly reducing the need for tamping or other maintenance activities



fig. 10: the HDS1 sleeper with a H-shape, showing a single (left) and double (right) fixation

- very resilient fixations: by applying a soft UBP ("Underbaseplate pad"), it is possible to introduce a highly resilient element in the track system, excluding the need for a USP. It is however essential then to have a precompression mechanism for the application of an initial compression to the elastic pad, so that the actual vertical deflection of the track remains limited when trains are running over, for obvious reasons of safety

It needs to be emphasized that the introduction of such measures will lead to an initial reduction of the vibration levels after installation (compared to the situation before, when existing), mainly due to the renewal of the track itself: new rails, new sleepers, new ballast which is well tamped, etc. But as explained, the big advantage lays in the long-term track stability, i.e. there will practically not be any degradation of the track over time, thereby reducing the need for regular maintenance, and increasing the comfort level for vibrations in the direct surroundings of the track.

As to the mitigation measure for switches (crossings):

Switches (crossings) are a typical source of complaints regarding vibrations in track networks such as Infrabel. Vibrations are generated here mainly because a specific part tends to come into resonance / amplification: the triangular point piece where the rails come together is excited vertically during a train passage, and its excessive movement may generate disturbing vibrations in the direct surroundings. By changing the fixation setup of this triangular point piece, through the use of resilient elements which are precompressed using a similar mechanism as for curves, it is possible to improve the situation. This improvement stays however limited to approx. 2dB in the lower frequencies which are typical for freight

trains. Higher improvements (5 to 10dB) can be reached at higher frequencies which are more typical for passenger trains, so in case of a mixed use of the track (freight / passenger), this system may still be considered beneficial. It is possible to reach higher improvements also at the lower frequencies, but only when the axle load of the trains stays within narrow tolerances, say +/- 15%. In that case, the resilient elements involved can be determined in a more optimized manner, and a more resilient pad could be used, leading to a lower resonance frequency of the setup. It must however be clear that an in-depth study, combined with adequate lab tests, is a necessity to come to a good design for every other type of track / trains.

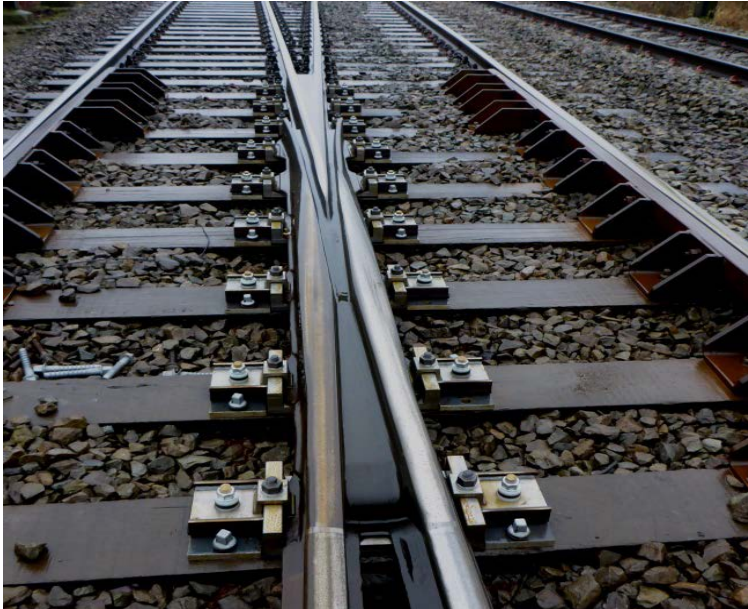


fig. 11: installation of the CDM-Elastiplus system in a crossing in Remersdaal (BE)

1.2.6. New developed mitigation measures in the propagation path

Among different isolating solutions for mitigation of train-induced vibrations that exist in the literature, this study focuses on barriers covered with resilient material as a mitigation measure in the propagation path.



fig. 12: coated ground wall, built in Arnhem, The Netherlands; in the left picture the top of the resilient layer can be seen (two 60 mm black slabs, partially covered with sand), just where the ground wall surfaces and continues as a ground retaining wall (with sound absorbing panels)

The mitigation of traffic-induced vibration by barriers is termed as a dynamic soil-structure interaction problem combined with a wave scattering and wave transmitting mechanism. The presence of an isolating barrier between the vibration source and the receivers reduces the vibration level at the receiver points by reflecting and scattering the incoming waves and by affecting the wavelength of the incoming waves as they are modulated by the barrier layers.

In designing an efficient isolating barrier, the main objective is to reduce the energy of the ground born vibration by increasing the wave reflection caused by the impedance jump on the soil-barrier interface as well as the vibration scattering due to the bending waves of the barrier as a infinitely long beam. This mechanism clearly shows how the barrier performance can be improved by increasing its depth.

In the case of low frequencies so typical for vibration from freight trains, the impedance jump between soil and barrier depends not so much on the difference in density between barrier and soil as on the **relative stiffness between the barrier and the soil**. For that reason, more effect can be expected from adding a, soft, for instance elastomer layer, than a light, for instance polystyrene layer.

In practice, the construction of a very deep barrier becomes more difficult and consequently, more expensive with increasing depth. The idea is to improve the efficiency of the barrier without increasing its depth. For this purpose, a concrete barrier covered by a layer of resilient material is proposed. It is shown that a combination of a concrete barrier with a layer of resilient material is more efficient than a pure concrete barrier.

Design of a coated ground wall comes down to balancing transmission and diffraction, the two ways that waves travel to the backside of the wall. Transmission of vibration is influenced by the thickness and stiffness of the elastomer, the diffraction by the depth of the wall. No need to deepen the wall if transmission is the dominant path, or thicken the layer if diffraction is.

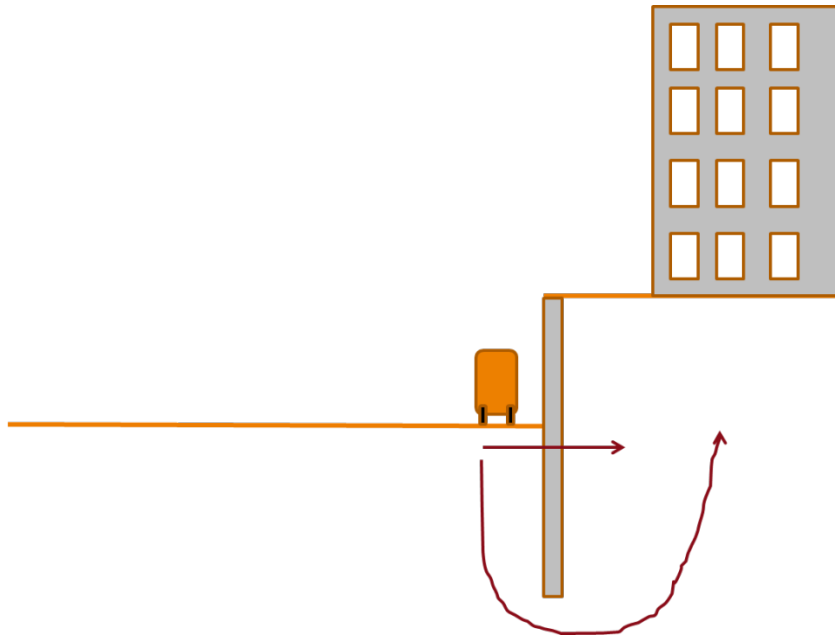


fig. 13: balance between transmission and diffraction

With modelling, lab tests and field tests, the reflecting (transmission reducing) effect of the resilient layer in sandy soils was studied and proven. Different layer configurations have been tried and an optimum found.

Diffraction underneath the wall has been studied here to a certain extent but is not different from diffraction under any barrier, notably “empty” barriers, for which lots of studies are available already. The focus of our studies lies on the reduction of transmission (of concrete barriers), which is new, and which is beneficial as concrete barriers are easier to construct than, for instance, empty barriers.

The conclusions about the reduction in transmission (which is different from the insertion loss, as that also includes the contribution of diffraction) in the frequency range for freight trains vibration are:

- A concrete wall of about 1 meter thickness in a sandy soil in itself will introduce a transmission loss of about 3 to 7 dB, depending on frequency.
- A resilient layer of 12 cm, with the lowest dynamic stiffness possible given the needed static load, adds about 6 dB to that, depending on frequency.
- Every doubling of the resilient layer adds about 3 dB.
- Topology does not play a role: the resilient layer can be placed on either side, or even divided between the two sides of the wall (generating a sandwich). There is no benefit nor a penalty.

Note: in the studies and tests, the water table was below the foot of the wall.

Building a ground wall with an elastic layer in a sandy soil is not totally trivial. Until now, the only successfully applied method has been a “mining” method.

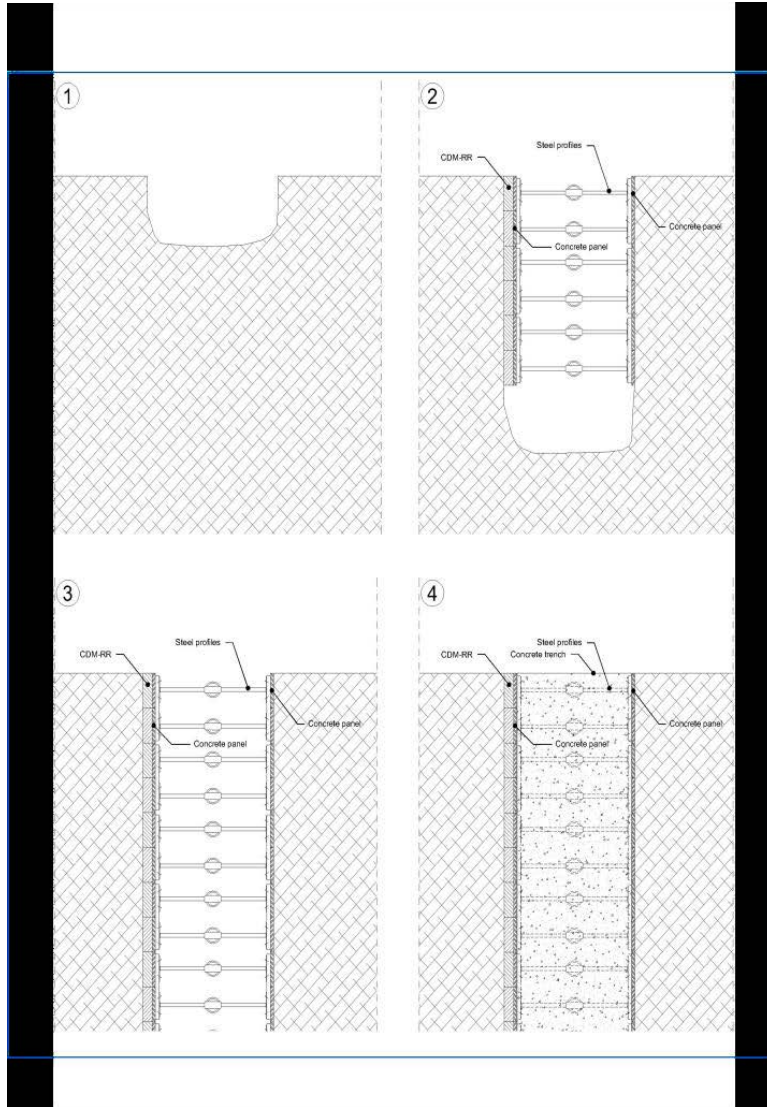


fig. 14: building a coated ground wall