

Effektiva tågssystem för godstransporter
- Underlagsrapport -

**Noise and vibration aspects on
railway goods transportation**

(Teknik för mindre buller och vibrationer)

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8 NOISE AND VIBRATION ASPECTS ON RAILWAY GOODS TRANSPORTATION

8.1 INTRODUCTION

Increasing the capacity of the railway goods transportation system by raised vehicle speed and load capacity in terms of axle load has potentially negative consequences. The increased noise and vibration emission may for instance be difficult to combine with increasing demands on an environment free from excessive noise and vibration. The increased vibration exposure for the goods increases the risk for damaged goods. The wear of track and the running gear may increase due to increased vibrations. Figure 1 gives a schematic overview of the noise and vibration generation and its implications.

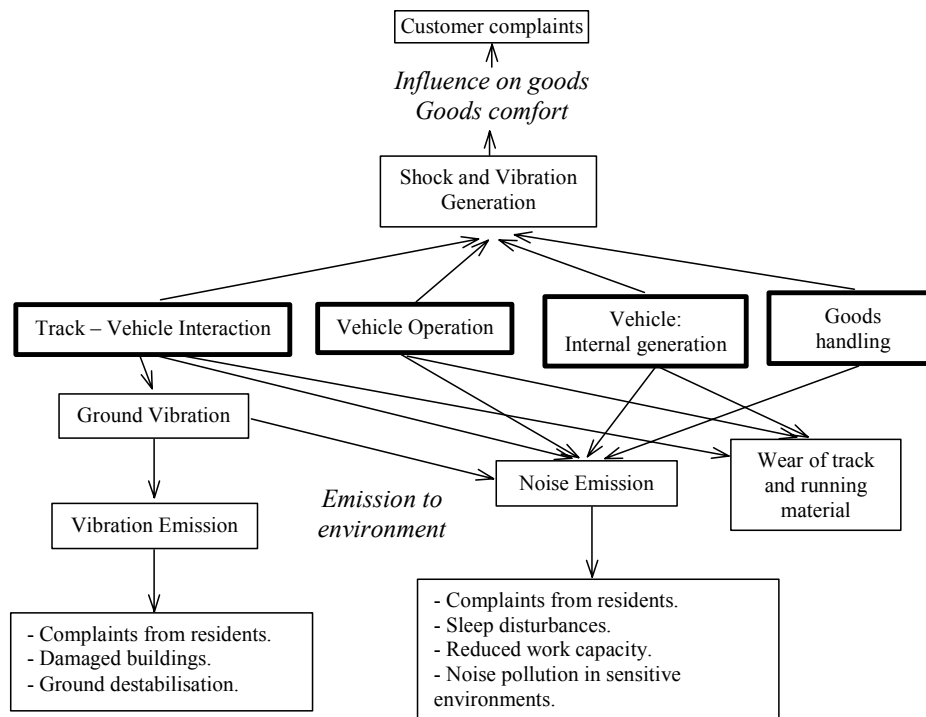


Figure 1 Schematic overview of implications of noise and vibration emitted from railway goods transportation systems.

8.2 NOISE EMISSION FROM RAILWAY LINES

Railway vehicles, for passenger as well as for goods transportation, generate both interior and exterior vibration and noise. The emitted external noise does not cause noise levels so high that the risk for impaired hearing among nearby residents is significantly increased. The noise from passing trains is rather a cause of irritation and sleep disturbances that affects the ability to perform well at home and at work. Sleep disturbances is a common consequence of train passage noise and in particular of railway goods transportation since part of the goods transportation is performed during night.

Goods transportation during night decreases the efficiency of the railway goods transportation system. To reduce the noise disturbances the allowed maximum speed in residential areas has been reduced. Hence, a reduced noise emission making it possible to increase the allowed maximum speeds would improve the transportation efficiency.

Another common measure taken to reduce the noise exposure in residential areas is to install noise screens. Traditional noise screens are expensive and considered unaesthetic and is therefore used only in lack of good alternatives.

Yet another measure to reduce noise exposure is to improve the noise insulation of the buildings. This means for instance using high quality windows and doors with high noise reduction indices. Because of the large number of exposed buildings this alternative is also considered as expensive.

8.2.1 Railway noise sources

In an electrically powered railway system, such as the Swedish, the main contributors to exterior noise are the wheel-rail system, the brake and coupling system on the wagons and the locomotive with its traction system. In addition to these an important noise source in goods transportation systems are empty wagons. Empty wagons frequently have loose parts of various kinds that emit lots of noise when set into vibration. On loaded wagons the vibrations of these parts are constrained.

In the neighbourhood of goods terminals and shunting yards the goods handling and shunting operations usually cause very disturbing and high level impact noise. These noises are, of course, particularly cumbersome during night.

8.2.2 Reduction of railway noise emission

Measures to reduce railway noise emission can be applied to the vehicle (the running gear) or to the track. Since this investigation deals with the railway goods transportation system focus is put on measures on track and running gear and not on wayside measures such as noise screens.

Measures on running gear

The noise generated by goods transportation is partly due to the low technical standard of the running gear. A substantial reduction of the noise emission, in the range say 10 – 20 dB, can be attained by simply implementing existing technology already in use in trains for passenger transportation.

One important noise source is wheel vibrations induced by rough wheel and rail surfaces. The noise radiated by the wheel is dominated by contributions from resonant wheel vibrations. In current (2003) designs available on the market there are several wheel resonances having resonance frequencies in the range, 1000 Hz – 3000 Hz, where the human hearing is most sensitive. A German investigation worked with the assumption that the perceived noise disturbance is reduced if the wheel resonance frequencies are shifted to the region above 3000 Hz [1]. One investigated design had a wheel web axially stiffened with a tangential sinuousoidal cross section. Simulations indicate a possible 6 dB(A) wayside rolling noise level reduction at a train speed of 100 km/h.

Another proven way to reduce the noise generation is to use silent braking systems. Traditionally freight trains have been equipped with cast iron block brakes whereas passenger trains are equipped with disc brakes. Experience has shown that cast iron block brakes already after a short usage cause wheel corrugation that generates noise in the region 800 Hz – 2000 Hz. Measurements, see for example [2], show sound pressure level differences at typically 10 – 15 dB in this frequency range. An alternative to the more complicated and expensive disc brakes is to exchange the cast iron blocks to sinter metal or composite blocks. Both these alternatives have been shown to be acoustically comparable to disc brakes. Negative aspects with the alternative material blocks are the poor heat conduction properties and the poor friction properties in cold and humid conditions. In spite of this several European national operators have decided to replace the traditional cast iron blocks with the alternative material blocks. A German study [3] indicates a possible 30 % – 40 % cost reduction for wayside noise reduction measures.

Another noise reduction measure may be a modified wheel suspension system that reduces the amplitude of the dynamic wheel-rail contact forces.

Noise generated by loose equipment and parts of the wagons, for instance chains, bars, lids and doors are reduced simply by systematically introducing a number of existing simple measures preventing the noise generation. Simply by avoiding metal against metal contact surfaces by introducing rubber will significantly reduce the noise generation. What is needed here is a systematic survey of sources and measures needed and then introduce these on all rolling stock.

The reason for not using modern high quality running gear is high initial costs. The goods transportation system operators are unwilling to invest the sums required to exchange the goods carrier wagons in use today. It might prove successful to introduce a differentiated tariff for using the track. Noisy rolling stock pay higher tariffs than silent do. Another important reason is the difference in regulations and standards between different countries. This is a serious problem since a specific goods waggon on its way to its destination may cross several borders between countries.

Measures on track

In principle there are two ways of reducing the noise emission from the track, to reduce the track vibration and to reduce the track noise radiation. Measures concentrating on reducing the track noise radiation, such as various types of screens, are usually expensive and are realistic alternatives only in particularly sensitive areas for example residential areas.

The most efficient noise reduction measures are usually directed towards the source region, in this case the wheel-rail contact. The rolling noise that is dominant in the absence of squealing is generated by the rough wheel and rail rolling surfaces. German

investigations [1] indicates a 15 dB(A) sound level difference between a rough, corrugated rail and a rail surface as smooth as possible to achieve in practice. Hence, large noise reductions are achieved by introducing a track surveillance program aiming at keeping the rail surface smooth.

One way to reduce the wheel-rail system noise generation is to increase the vibration energy dissipation. A number of different methods, ranging from viscoelastic layers to dynamic absorbers have been developed. Most of these suffer from either being expensive or being inefficient or impractical in field conditions. A potentially efficient and inexpensive method to dissipate rail vibrations, developed at MWL, KTH, makes use of contact friction forces. Evaluations at laboratory conditions indicated promising results with high loss factors. It still remains, however, to be optimised and evaluated in field conditions.

Another possibility is to modify the dynamic properties of the wheel-track system so that the vibration energy is removed from elements acting as strong acoustic radiators. A modified rail-sleeper-foundation system enabling the vibration energy to transmit into the ground rather than propagate long distances in the rail would reduce the rail contribution to the noise emission. This is an interesting possibility that deserves further attention. It is important though to limit the high transmissibility to the audible frequency range. For lower frequencies it is important to reduce the vibration transmission to the ground in order to limit the ground vibration emission to the environment.

Given a specific rail vibration level the radiated noise reaching a wayside observer can be reduced by decreasing the rail's ability to radiate acoustic energy. This is achieved by either reducing the area of the radiating rail surface or by introducing holes in the rail web short-circuiting the radiation. The effective radiating area can be reduced by acoustically screening the rail. Since the 1970s in Japan until today, 2003, a number of investigations, primarily Dutch and German, have studied the effects of using a ballastless track [4-6 and 7-9]. In the new track concept, developed for heavy haul and high speed purposes, the rail is continuously or elastically suspended on a concrete foundation. In the most far reaching designs a substantial part of the rail is embedded in rubber. In some solutions the radiating surface is reduced with ca 50 % implying a possible 3 dB reduction of the wayside sound power level, if all other factors are assumed unchanged. Another benefit from the ballastless design is that it efficiently isolates the vibrations from the structure below the rail. This, however, is negative for the noise emission since the rail vibration level will increase. In fact investigations performed by NS in the Netherlands show that ballastless track is not quieter than ballasted track.

Also in economic terms the ballastless slab track is claimed to be competitive to the traditional ballasted track. On the one hand it requires more initial investments on the other hand the maintenance and service costs are reduced. All together the service life costs are claimed to be lower than for the ballasted track and that the ballastless track is a competitive alternative for new lines whereas it is not for existing lines [10].

Finally the possibility to use low screens placed very close to the rail should be mentioned. Placing the screen close to the sound radiating source, i.e. the wheel-rail contact, drastically reduces the required screen height to levels that do not interfere with neither a wayside nor an onboard observer. Various solutions using screens with height 0,7 m have been tried in field conditions by the NS [7-9]. There is also a possibility to optimise the screens acoustically with respect to the frequency contents of the radiated

noise. This optimisation can be achieved by different designs of the screen top [11]. In principle the optimised screens make use of resonating elements tuned to strong frequency components in the source spectrum.

Measures at goods handling and shunting operations

In shunting operations high impulsive noise is generated when wagons are allowed to run into each other. The noise can be reduced by acoustical treatment of the couples and by introducing automatic shunting where unnecessarily fierce collisions are avoided.

Loading and unloading the goods include a number of possible noise sources. When trucks are used their machinery may emit noise. Trucks with diesel engines are significantly noisier than trucks with electric motors. The introduction of new goods handling systems can in combination with adapting existing noise abatement methods reduce the handling noise generation. Simply by performing the handling operations more gentle would significantly reduce the noise generation.

Suggestions for further research

As indicated above the noise emission can be substantially reduced by implementing existing technology on the running gear. Or as stated by P de Vos of the Nederlandse Spoorweg, "Designing new quiet goods wagon on the drawing table will not be the problem. But the major demand in Europe is for the development of usable workable and in particular low-cost retrofit measures" [12].

As far as the measures on the track is concerned there are a number of alternatives useful in sensitive areas. Three specific topics are suggested for further research,

- an optimised rail friction damper,
- the possibility to tailor the track so that as large part as possible of the rail vibration energy is absorbed in the ground-sleeper system and
- the possibility to introduce track-mounted noise screens should be further investigated.

8.3 VIBRATION EMISSION FROM RAILWAY LINES

A rail vehicle running on a track causes vibrations in the track structure as well as in the neighbouring ground. There are two basic generation mechanisms, - the moving quasi-static load and - the irregularities in the wheel-track system. Vibrations with frequencies above say 20 Hz is mainly restricted to the rail-sleeper system and cause noise radiation, see paragraph 8.2.1 above. Rail vibrations below 20 Hz can radiate significantly to the surrounding ground and cause annoying disturbances among residents and cause damage to track, embankment and neighbouring buildings. Two key factors for the low-frequency railway vibration emission have been found to be train speed and weight [13]. For high speeds close to a critical speed very strong ground vibrations or shakings have been shown to appear [14]. This, of course, is a severe constraining factor for any attempt to increase the efficiency of rail goods transportation systems by increasing train speed and axle load.

8.3.1 Disturbances caused by railway ground vibrations

The most important ground vibration disturbance is annoyance among wayside residents. This annoyance causes significant problems and costs for track owners. There are several studies performed to investigate the degree of annoyance caused by vibration from different types of transportation [15,16]. Based on the results standards such as SS 460 48 61 and policies such as Banverkets BVPO 724.001 have been published as frameworks for judging the severity of the annoyance. Banverkets policy, for instance, states that no one should have to suffer wayside railway vibrations higher than 2,5 mm/s (root mean square velocity value) in the bedroom during night and the long-term planning goal is a maximum rms velocity of 1 mm/s. In the standard SS 460 48 61, for evaluating the comfort in buildings, weighted velocities higher than 2,0 mm/s are categorised as “Likely to be annoying” and velocities in the range 1,25 mm/s – 2,5 mm/s as “Very annoying”. The Norwegian standard NS 8176:1999, which is probably the most elaborate, uses four classes A-D for rating the vibration comfort in buildings, see table 1.

Table 1 Classes used in Norwegian standard NS8176:1999 for rating the vibration comfort in buildings. Class A – High vibration comfort. Only a few people will perceive vibrations. Class B – Fairly high vibration comfort. People will to some degree perceive vibrations. Class C – Recommended limit for vibrations in new buildings and when new railway or road transportation lines are planned. Approximately 15 % of the people subject to vibrations according to class C will be disturbed by the vibrations. Class D – Recommended limit for existing buildings. Approximately 25 % of the people subject to vibrations according to class D will be disturbed by the vibrations. The weighted velocity v_w is the root mean square vibration velocity weighed with respect to the human sensitivity to vibrations. Weighting curves can be obtained from proper standards. The weighted velocity $v_{w,95}$ is the weighted velocity compared to which 95 % of the weighted velocity readings are lower.

Class	A	B	C	D
Maximum weighted velocity $v_{w,95}$ [mm/s]	0,1	0,15	0,3	0,6

In a survey initiated by Banverket the distribution of vibration levels in wayside buildings was investigated in a couple of regions. It was found that in some municipalities more than 5 % of the buildings within 150 m from the track have measured rms vibration velocity values higher than 2,5 mm/s and up to 40 % of the buildings have values in the range 1 mm/s – 2,5 mm/s. Hence, it is clear that annoyance due to railway ground vibrations is a problem that needs particular attention if train speed and axle load is increased.

It is also worth mentioning that annoyance due to vibration disturbances is a complex area of psychological investigations. It is, for instance, evident that the annoyance caused by various stimuli such as vibrations, noise, temperature etc interacts in a complicated way. Reduced noise levels may, for instance, cause increased complaints on vibrations. Noise from rattling windows is categorised as a noise problem but is often a consequence of vibrations transmitted through the ground.

8.3.2 Propagation of ground vibration

The severity of vibrations reaching a wayside building depends on a number of factors. The most important is of course the distance to the track. Another important factor is the ground dynamic properties. It is known that loose soils such as clay and gyttja leads to more low-frequent high amplitude vibrations than more firm soils. Other influencing factors are the soil depth to the bedrock and the existence of soil layers.

Not only the ground but also the building properties such as the foundation and height influence the vibrations propagated into a building. Measurements have shown that vibration amplitudes measured at ground level are lower than at the upper storeys. Buildings with piled foundations are less sensitive than those with floating foundations etc.

8.3.3 Reduction of vibration emission

Measures to reduce the annoyance due to railway vibrations can be implemented at the train, at the track, along the transmission path through the ground or in the receiving buildings.

The measures on the running gear are aiming at decreased vibration generation by reducing the wheel-rail force fluctuations. One example is the attempts to reduce the dynamic mass of the bogie by modifying the wheel suspension system. Since the wayside vibrations are mainly due to the quasi-static moving load the measures on the running gear are useful only in specific cases where vehicle dynamics is an important vibration source.

Measures on the track and its close neighbourhood mainly focus on either preventing the vibrations to radiate to the surrounding ground or on increasing the dissipation of vibration in the track region.

Examples on the first group of track measures are introducing soft rail pads, introducing continuous sleeper systems, i.e. ballastless slab track or increasing the mass and stiffness of the trackbed. Recent research performed by the division of soil and rock mechanics and the department of vehicle engineering have investigated the use of lime cement columns as a means to change the track properties to reduce vibrations and also as a means to screen vibrations along the propagation path [17].

8.3.4 Suggested research

The following section 3.4 is a summary of the state-of-the-art knowledge on railway induced ground vibrations with recommendations for future research. The material is written by A Bodare at KTH.

Introduction

Problems in connection with ground shakings get more and more attention as an environmental problem. The consequences of shakings are damages inside and outside buildings and less comfort for people exposed to the shakings. There have been cases where vibration related comfort problems have made buildings uninhabitable.

Traffic on railway lines may generate strong ground shakings particularly from heavily loaded freight trains. High-speed trains may under certain circumstances generate strong shakings in the ground. In some places temporary speed reductions have been imposed to decrease the level of shakings. It is always in areas with soft and very soft soil where

the strong ground shakings occur. West Sweden, the valley around Lake Mälaren (where Stockholm is situated), East Gothia and the river estuaries in Northern Sweden are especially vulnerable. All these areas have numerous populations.

Seldom the shaking creates structural damages to a building. They create mostly cosmetic damages on facades, outer and inner walls etc. These damages are, however, many times conspicuous and lower the value of the building, something, which is serious for the owner of the building. The big problem with ground shakings seems to be the sensation of low comfort for the residents. This means that ground shakings generated by traffic will have an increased importance as an ordinary environmental problem in the near future as railway lines penetrate densely urbanised areas all hours of the day.

Train traffic

Swedish Rail Administration has since many years measured train traffic shakings when neighbours to a line complained on disturbing shakings. The Administration has also supported research and development at the Technical Institutes and Universities in this field.

Recently ground shakings induced by the high-speed train X2000 on the West Coast Line have stirred great interest. It has been shown that high speed trains can run with a speed that is higher than the Rayleigh wave and shear wave velocity of the ground adjacent to the rail way embankment. Very strong ground shakings is then generated in the ground. The speed of the train is also close to the so-called critical speed, which occurs because of the interaction of the embankment and the soil in which it is founded. At the critical speed the displacement and accordingly the velocity and acceleration of the embankment will be large. Perhaps the movement may be as large as to threaten the stability of the embankment. Swedish Rail Administration has spent large resources on a project named "High Speed Lines on Soft Ground", which was reported in 1999. Several organisations in Sweden and Norway participated in the project. Investigations were performed south of Gothenburg in a soil consisting of soft clay and gyttja. The conclusions of the project were that the stability of the embankment was not in jeopardy but that the embankment had to be stabilised. The stabilisation was later performed and the movements of the embankment became only 10 % of their value before the stabilisation. Increasing the speed of trains will cause these problems on more sections than there is today.

The environmental problems with ordinary passenger and freight trains are probably more important than those of high speed trains. However this leads to the consequence that higher frequencies of the shakings have to be taken into account than normally is done in geotechnology as a human being is sensitive for vibrations at frequencies up to 80 Hz. Normally only frequencies up to 20 Hz are studied in geotechnology.

Chain of influence

Many ground shaking problems comprise a chain of influence i.e. a source emits energy into a medium which transmits the energy to an object, receiver, which is excited. For geotechnical problems it is customary to regard the train, rails, pads, sleepers and the embankment as the source. The medium consists of the soil in which the embankment is founded and further out the soil that is normally layered and may consist of different geological materials. The object is often a building or a collection of buildings with

inventories. It may also be constructions, belonging to the railway as the electricity poles etc.

It is important to recognise that the interfaces between the source/medium and the medium/object will create interaction between the source/medium and medium/object, which in turn give rise to mechanical phenomena. The critical speed mentioned above is such a phenomenon of the interaction between the source and the medium. The following is a summary of the links in the chain of influence. Keywords given in italics in parenthesis are used as reference in the tables below.

Source

Forces from the train wheels acting on the rail are the ultimate sources of ground shakings in the vicinity of the railway line. The movements and the internal forces of a train set give rise to these forces together with the forces generated by the interaction between the train and the sleeper/embankment system. Important entities deciding the properties of the emitted waves are the masses of the locomotive and the cars and their relative distance (*axle loads*), the springs between wheel (*wheel springs*) and cars together with the speed of the train (*train speed*). The velocity of the train may vary (*accelerated train motion*). There are observations that suggest that a train braking emits strong ground motion.

There are several different mechanisms contributing to the emission of waves into a railway line surroundings. The static load of the train is transmitted through the axle loads to the rail/sleeper/embankment system and out to the surroundings. There will be a depression, settlement, moving with the train. A passenger moving with the train will see the depression not changing with time. The shape of the depression changes with the speed of the train and can reach several tens of meters in the surrounding (*dynamic depression*). The depression deepens and becomes broader with increasing train speed. As the train speed approaches the Rayleigh wave velocity the depression might be deep and wide. Above the Rayleigh wave velocity the dynamic depression will contain at least one shock front.

The rail contains inhomogeneities of two different kinds; in stiffness and in geometry. These create forces of reaction in the embankment and create waves in the surrounding. The waves are observed both by a passenger moving with the train and an observer on the ground. Geometrical inhomogeneities are foremost irregularities of the rail. The irregularities have very different scale of lengths (*wavelength*), varying from mm to kms. When a train passes such irregularities time varying forces appear with very different time scales, frequencies (*irregularities*).

The passage of the train through curves will create a vibration source with a strong horizontal component together with a vertical component. This is kind of an accelerated movement, which was mentioned above.

Another inhomogeneity in stiffness and geometry is switches. The passage of a train over it will force it as a stationary source for mechanical waves (*switch passage*).

Inhomogeneities in stiffness appear chiefly due to the sleepers. Even if the rails were completely smooth a wheel would create time varying forces since the rails are supported only over a part of its length. The other part is not supported. During the passage of one wheel a sleeper will transmit a time varying force in the shape of a pulse into the embankment (*sleeper pulse*). When several axles pass one sleeper the pulses will repeat each other with a time distance of $T_{wi} = b_i/V$ (b_i is the distance between two

consecutive wheels and V is the speed of the train). The frequency spectrum of all the pulses is called the load spectrum, (*load spectrum*).

As the train passes over the sleepers it will excite the embankment with a periodic force following the train. The period is a/V (a is the sleeper distance and V the speed of the train). Its inverse will give rise to the sleeper passing frequency $f_s = V/a$ (*sleeper passing frequency*).

When the train is moving the cars and the engine will move individually back and forth and from one side to another creating forces of reaction which are emitted to the embankment and out in the environment (*train vibration*).

The embankment consists of two parts the upper part and the lower part. Both usually contain ballast material. The behaviour of the ballast to dynamic loads is not very well known compared to ordinary geo materials. Some research has been performed and is reported in literature. The strains are expected to be high during a train passage. The material will then deform in a non-linear elasto-plastic way and the internal damping will be high (*ballast material*).

The profile of an embankment has the same dimensions as the wave lengths of the emitted waves and will probably therefore affect the waves by filtering out some frequencies and amplifying others. The size of an embankment changes often as a train is moving on it. A train running with 180 km/h will in only 5 seconds pass a distance of 250 m. In that distance the height may change appreciably (*embankment changes*). A special kind of embankment change is when the train passes the end of a bridge from the bridge structure into the soil (*bridge foundation*).

It may be expected that a running train emits waves differently in different directions (*direction effects*) because some of the lengths of the emitted waves are of the same order as the length of the train or shorter.

Interaction between source and surrounding soil

The flexible embankment and the surrounding soil interact dynamically. If the surrounding medium is changed the emitted waves would also change. And the disturbances in the environment would differ in character. It should be possible to talk about "Interaction of Source-Soil" (ISS), cf. Soil-Structure Interaction (SSI) in earthquake engineering.

An obvious example of the interaction process is the phenomenon of critical speed. A train moving with a slowly increasing speed will cause the rail and the embankment to deform under itself. The displacements will gradually increase until the train moves with the critical speed. If the speed of the train is still increased the displacements will decrease so at very high speeds the displacements will be zero! The displacement at the critical speed can be appreciable. The process is similar to the resonance phenomenon. However the displacements do not appear because of an exciting frequency but of an exciting speed. The formula for the critical speed contains entities both from the embankment and the surrounding soil. For very soft soils in western Sweden and the embankments used the critical speed is around 235 km/h. (*critical speed*).

Close to the embankment the soil will be highly strained. It will then deform in a non-linear fashion, which will affect the movement of the embankment and the character of emitted waves. Soil material softens with strain. The internal damping increases with strain. The softening and the dissipation is more pronounced in friction material (sand, silt) than in cohesive material (clays). (*non-linearity in stiffness and damping*).

It is also possible that the interaction between the embankment and the soil leads to instability of the train motion. The motions of the embankment will then forever increase beyond limits (*instability*).

Even the interface properties will in reality change with the length of the embankment as was noticed above.

Surrounding soil

Propagation of mechanical waves depends on several properties of the soil material i.e. stiffness, specific impedance, internal damping, densities, propagation velocities and their variation inside the material. (*material properties, inhomogeneities*). It is expected that the non-linear properties of the material properties only affect the soil in the close vicinity of the embankment. Further out, where the amplitudes are small enough, the soil will behave linearly. However the material will be inhomogeneous as it may consist of a dry crust at the surface, clay material below it and further down a sandy, silty soil material. There might be in a clay deposit embedded sandy silt lenses. Also in the horizontal direction there will be changes of the material as the depths to the different layers may change as well the depth to solid rock. Even when there is a deep deposit of soft clay the clay will change its properties with depth because the properties are dependent of the overlying stress.

Changing properties with depth cause the waves to show dispersive behaviour i.e. the velocities of propagation of the different waves will change with frequency or wavelength (*dispersive effects*). A short pulse close to the source will be elongated during its propagation through the soil material. Connected to dispersion is the appearance of resonance frequencies of a soil layer. A layered soil has several resonance frequencies, which might play a role during a passage of a train over a layered soil. (*profile resonances*)

Usually the waves are attenuated with distance from the source because of geometrical spreading and internal damping. The waves have different characters depending if they are close to the source (near field, i.e. distances equal or less than the extension of the source) or if they are far away from the source (far field). A freight train may be several hundred meters long while a commuter train 30-40 meters long. It is often easier to analyse waves in the far field than those in the near field. (*attenuation*). The dispersion effect will also affect the attenuation.

Connected to attenuation is the effect of spreading when a wave encounters an obstacle in the soil. The spreading depends of the frequencies or lengths of the waves compared to the dimensions of the obstacle, (*obstacle spreading*).

There is also the phenomenon of focusing of waves, which may be accomplished in mainly two ways. First the rock surface below a soil material may be slightly concave and act as a mirror to down going waves. The rays of the waves will be reflected by the mirror and focused to points close to the surface; just as in optics. The other way is that the variation of the soil layers, even if they are completely horizontal cause the rays to refract (bend) so they will meet in a spot close to the surface of the soil. This is similar to how light rays are bent in an optic fibre. (*focusing*)

Topography of an area affects the strength of ground shaking. It might amplify, at top of hills, or reduce, at bottom of depressions, the motions compared to level ground. The motions of an edge of a river are expected to be amplified, (*topography*).

A special problem for the Nordic countries is the frozen ground in winter. (*frozen ground*)

Interaction between Soil and Object

An object, building or another kind of structure, interacts with the surrounding soil. It is well known that the foundation of an object does not move with same displacements as the surrounding soil, (*differential motion*). In contrast to the source soil interaction where the source is flexible the object usually encountered in train traffic problems is much more rigid. The foundation itself can, if rigid body motion is assumed, move in six different modes (three translations and three rotations) and will show one resonance frequency and a substantial damping caused by the radiation of waves from the foundation for each mode of vibration. (*foundation resonance, radiation damping*). These effects are manifestations of the interaction between the soil and the object. The problem can be appreciated as a spreading problem. (*object wave spreading*).

Foundations can be of different types. It may be a simple plate resting close to the soil surface, a basement in one or several floors or a plate supported by piles of different configurations etc. The problem with interaction between waves and structures, soil structure interaction (SSI), has been and is studied thoroughly in earthquake engineering.

Object

An object is excited by waves arriving from different directions as the source is moving on the embankment. The rays, which will arrive at a given time, have been emitted from the train at different times (it is similar to the sky where we spot the stars and galaxies at positions they had a time when the light rays were emitted; today they have other positions).

The object imagined mounted to a completely rigid foundation will have several resonance frequencies. The rigid mounting removes the influence of the foundation. The interaction between the foundation and the rest of the object will change the resonance frequencies and their internal damping. (*object resonance, object damping*). The object damping is usually much less than the foundation radiation damping. A consequence of existing resonance frequencies is that the object will filter the frequency contents of the incoming waves. Some frequencies may easily excite the object but others not.

The study of the dynamical behaviour of structures is well developed by an academic subject of its own; structural dynamics.

Inventories

The chain of influence concludes with the inventories of the object. In this context human beings may be included in the inventories. Other inventories may include sensitive equipment in hospitals and industries particularly electronic industries and electronic devices belonging to the operation of the railway line.

As this part discusses the geotechnical problems in connection with train traffic induced ground vibrations we leave the chain of influence here.

Summary of technical items discussed in the preceding sections

Below follows tables 2 - 6 with the technical items, which were discussed in the preceding sections. **F** stands for facts that can relatively easy be obtained from different sources. **D** stands for development work, i.e. the theories are known but they have not so far been applied to train traffic induced ground vibrations. After the letter **D** the area of known theories is mentioned. **R** stands for research is needed, i.e. basic knowledge is missing both on the theoretical and the applied level. **W** stands for weight, which means non-linear behaviour of the material is important. Non-linear behaviour of soil materials is in principle known but the consequences for train traffic induced ground vibrations are not known. For ballast even the non-linear materials properties should be better known. **S** stands for speed, which means that the consequences of different speeds are not well known.

Table 2 Railway vibration sources.

Item	Fact	Develop	Research	Weight	Speed
Axle loads	F				
Wheel springs	F		R	W	
Train speed	F				
Rail irregularities	F				
Sleeper frequency	F				
Load spectrum	F				
Accelerated train motion			R		
Dynamic depression			R	W	S
Switch passage			R	W	S
Sleeper inhomogeneity pulse			R	W	S
Train vibration		D			
Ballast material			R	W	
Embankment changes			R		
Bridge foundation			R		
Direction effects			R		

Table 3 Interaction between source and surrounding soil.

Item	Fact	Develop	Research	Weight	Speed
Critical speed			R	W	S
Non-linear stiffness			R	W	
Non-linear damping			R	W	
Instability			R	W	S

Table 4 Wave propagation.

Item	Fact	Develop	Research	Weight	Speed
Material properties, inhomogeneities		D			
Dispersive effects		D			
Profile resonances		D			
Attenuation		D			
Spreading from obstacles		D			
Focussing		D			
Topography			R		
Frozen ground			R		

Table 5 Interaction between soil and object.

Item	Fact	Develop	Research	Weight	Speed
Differential motion			R		
Foundation resonance		D			
Radiation damping		D			
Object wave spreading		D			

Table 6 Object.

Item	Fact	Develop	Research	Weight	Speed
Object resonance, damping		D			

Conclusions

Tables 7, 8 and 9 summarize the needed research and development task in 1st, 2nd and 3rd priority.

Table 7 1st priority research tasks on railway vibration.

Task	Develop	Research	Weight	Speed	Area
Static depression		R	W	S	Source
Switch passage		R	W	S	Source
Sleeper inhomogeneity pulse		R	W	S	Source
Ballast material		R	W		Source
Critical speed		R	W	S	Source-soil interaction
Non-linear stiffness		R	W		Source-soil interaction
Non-linear damping		R	W		Source-soil interaction
Instability		R	W	S	Source-soil interaction

Table 8 2nd priority research tasks on railway vibration.

Task	Develop	Research	Weight	Speed	Area
Accelerated train motion		R			Source
Embankment changes		R			Source
Bridge foundation		R			Source
Direction effects		R			Source
Topography		R			Wave propagation
Frozen ground		R			Wave propagation
Differential motion		R			Soil-object interaction

Table 9 3rd priority research tasks on railway vibration.

Task	Develop	Research	Weight	Speed	Area
Train vibration	D				Source
Material properties, inhomogeneities	D				Wave propagation
Dispersive effects	D				Wave propagation
Profile resonance	D				Source-soil interaction
Attenuation	D				Wave propagation
Obstacle spreading	D				Wave propagation
Focussing	D				Wave propagation
Foundation resonance	D				Soil-object interaction
Radiation damping	D				Source-soil interaction
Object wave spreading	D				Wave propagation
Object resonance, damping	D				Soil-object interaction

8.4 Goods vibrations – Goods comfort

Clearly, the first priority for the customer is to have the goods transported to its destination without delay, without damages and to a reasonable price. This part deals with goods comfort, or the condition of the goods, during transportation. A competitive railway goods transportation system must be able to guarantee a transport that does not damage the goods. A high goods comfort must be offered.

There are many examples on goods being sensitive to environmental factors. Food and groceries for instance are sensitive to climate factors like temperature. Some types of goods, for example precision instruments, are sensitive to shock and vibration. For this reason a competitive transportation system must be able to offer a diversity of alternatives satisfying the customer requirements. Experience shows that shock and vibration is the single most important cause of goods damage. Therefore focus is put on shock and vibration related damages.

8.4.1 Economic impact of damaged goods

The economic value of goods damaged during transportation is large. Based on data from insurance companies over the period 1986 – 1996 it is estimated that Swedish industry lost 1000 – 2000 MSEK each year in direct costs (overhead and goodwill not included) due to goods damaged during transport, [18]. The true value is even higher since only part of the goods damages are reported to the insurance companies. Also the above value only includes the damages covered by the insurances.

An interesting fact is that most investigators consider a large part of the transport damages to be avoidable. In Sweden 70 – 75 % of the damages are possible to prevent with fairly simple measures. The obvious conclusion is that large savings can be made by modifying the transportation system to reduce the number of goods damages. Therefore an important task is to investigate the causes for goods damages and find methods to avoid them.

8.4.2 Goods damage mechanisms

A number of vibration related damage mechanisms leading to certain types of damages have been identified [19].

Immediate damage caused by exceeded maximum stress or maximum displacement leading to failure. A typical scenario is a package dropped to the ground during loading, leading to a shock when the package is retarded against the ground. If the retardation is sufficiently large the inertia forces may lead to goods damage due to exceeded maximum stresses. Another example is jerks caused by improper handling during switching or during running by insufficiently tied coach couplings.

Accumulated damage caused by repeated, cyclic, stresses leading to wear or material fatigue. Typically these cyclic vibrations are generated in the vehicle power train. Unbalance vibrations in the running gear is one typical example. In addition to material fatigue cyclic stresses may lead to loose parts for instance screws. Hence this type of accumulated damage often precedes immediate damages leading to failure. In combination with improper loading the vibrations may also lead to worn surfaces on the goods when the goods rub against other structures, see below.

Shaving and rubbing caused by relative motion, or sliding, between the carrier and the goods or between parts of the goods. The goods may then be damaged by the contact forces, i.e. friction, in the contact surface between the goods and the carrier. During railway transportation this mechanism is usually caused by the shocks sometimes experienced during switching or during running with loose couples. Also note that if the sliding goods motion comes to a sudden end the consequence may be an immediate damage.

It is often noticed that sliding cargo is a frequent cause of damages. When the carrier experiences a horizontal shock the goods will, if the inertia forces are large enough, slide relative to the carrier. The sliding may directly damage the goods (shaving and rubbing) or indirectly if the goods abruptly run into an obstacle (immediate damage). Vibrations do, due to its oscillatory character, not directly set the cargo into sliding motion. Indirectly, however, vertical vibrations are known to reduce the effective friction force between the carrier and the cargo. The situation is particularly bad when the goods perform resonant vibrations. The risk for sliding cargos is reduced by using high friction contact surfaces, avoiding excitation of resonant cargo vibrations at for instance the sleeper passing frequency and by tying the goods to the carrier floor.

8.4.3 Goods sensitivity to shock and vibration

One important part in understanding goods damages is knowledge on acceptable shock and vibration levels. There are several attempts to classify goods with respect to its shock and vibration sensitivity. In table 10 one such shock sensitivity classification, obtained from [19], is shown. The values given in table 10 tries to classify the ability of the goods to resist damage due to shock.

Table 10 Classification of goods ability to resist shock [19].

Acceleration [g]	Description	Example
0 - 20	Extremely sensitive	Precision instruments with mechanical suspension
20 - 40	Very sensitive	Instruments and electronic equipment in stiff frames, needle-suspended instruments, navigation equipment, Cathode ray tubes, light bulbs.
40 - 60	Sensitive	Electro-mechanical equipment, cashier machines, cooling equipment fridges, relays.
60 - 85	Moderately sensitive	Radio and TV, optical equipment, electronic machines and measurement instruments, domestic appliances.
85 - 110	Relatively insensitive	Glass, porcelain, accumulators, heat exchangers
110 - 200	Insensitive	Machines, motors, transformers, bottles

8.4.4 Goods securing guidelines

Guidelines for securing goods in different transportation modes also provide valuable information. Using the guidelines the transport operators can secure the goods to ensure safety conditions sufficient to prevent damages to the goods, persons and the vehicle at non-exceptional events. Table 11 is a short summary of the dimensioning accelerations that is used for some transportation modes.

Table 11 Typical dimensioning maximum accelerations for securing cargo. Accelerations obtained during handling and exceptional events such as accidents are not considered. Data are taken from [20].

Transport mode	Org	Horiz acc [g]	Vert acc [g]	Comments
Road	TSV	1 / 0,5 / 0,5	1	Horizontal: Forward/Backward
Railway - vagnlast	SJ	4 / 4 / 0,5	1	Horiz: Forward/Backward/Lateral
Railway - combi	SJ	1 / 1 / 0,5	1	Horiz: Forward/Backward/Lateral
Sea (North Atlantic)	IMO	0,4 / 0,4 / 0,8	1	Horiz: Forward/Backward/Lateral

It is noticeable that the railway guidelines (together with sea) are the most restrictive of the four compared transportation modes. This is said to be a disadvantage for the railway transportation system since the cost for securing the goods is increased. Another

disadvantage is that the difference in rules reduces the flexibility of intermodal (eg road – rail – road) transports.

8.4.5 Shock and vibration measured during transportation

In order to reduce the number of goods damages knowledge on the shock and vibration exposure during the different transport phases is necessary. The following paragraphs provide some information, collected in literature, on shock and vibration exposure in various transport situations.

Shock and vibration exposure during railway transportation

The values presented in table 10 should be compared with values measured during transportation. During railway transportation the acceleration peak value rarely exceeds 4g ($1g = 9,81 \text{ m/s}^2$). In single events like switching substantially higher values, say 10g – 20g, can be obtained [19]. According to table 10 this indicates that if single events with very high accelerations can be avoided only the extremely sensitive goods is liable to suffer immediate damage due to shock exposure.

The large acceleration values are reached at particular events like,

- switching, where the carriers are allowed to run into each other.
- insufficiently tied couplings causing strong longitudinal jerks.
- wheel flanges impacting on the rails during for instance bogie hunting.
- passing poor track sections etc.

Some of these events should be considered as handling related events that can be influenced by modifying the handling routines.

Shock and vibration exposure during air and road transportation

The shock and vibration exposure to goods transported by road is comparable to that by rail, [19]. The lowest exposure is found in aircraft. The peak acceleration during violent manouevers is at most 0,6g, [19]. At very careless landings the peak acceleration can reach 5g, [19].

Shock and vibration exposure during handling

Handling usually causes the highest shock and vibration exposure. Loading and unloading the goods are critical operations. Loading and unloading containers with trucks are known to be able to produce peak acceleration values as high as up to 35g – 40g, [19]. Hence, reducing the acceleration exposure during handling will drastically reduce the goods shock and vibration exposure and is therefore an important task.

Shock and vibration measurement and evaluation

It is a difficult task to measure and evaluate goods exposure to shock and vibration. The problem is that the acceleration measured by an accelerometer mounted on the carrier is a local value that may not be representative for the acceleration of the goods. It has been shown that, due to resonances and strong local vibration fields, the locally measured acceleration values vary a lot with location. For that reason it is an important to find methods to measure and evaluate representative goods accelerations. There are a number of issues the research should focus on.

- How should the measurement positions be selected?
- How should the measured data be processed to obtain a representative acceleration value?
- Is it possible to estimate the shock and vibration exposure to goods inside packaging from accelerations measured on the carrier?
- How can the measured value be used as a measure of the probability for goods damages?

The investigation reported in [20] put some focus on goods sliding on the carrier surface and gives some valuable conclusions on how representative measurements can be achieved. It is, for instance, suggested to low-pass filter the accelerations using a filter with 8 Hz limit frequency. The filter is claimed to remove the effects of local vibrations and resonances and provides an acceleration representative for the whole carrier. On the other hand shock and vibration measured on part of the carrier is for sure important for the comfort of goods located on this part. In this situation the problem is to evaluate the effects on the goods.

8.4.6 Influence of shock and vibration on goods

Vibration testing means that the effects of shock and vibration on a product are tested. In the test the product is exposed to a predefined, sometimes standardised, schedule of shock and vibrations. Typically the schedule is designed using information on the shock and vibration environment for the product during transportation and operation. After the test the product is checked with respect to its function and possible damages caused by the test. Usually the test results are used for improving the product design so that it can resist its typical shock and vibration exposure. The results are also valuable for providing information on how and at what shock and vibration exposure the product is damaged.

8.4.7 Reducing the effects from shock and vibration exposure on goods

In principle there are a number of possibilities to reduce the shock and vibration related goods damages.

- The goods shock and vibration exposure can be reduced by a modified carrier design.
- The sensitivity of a product to shock and vibration can be reduced by a modified product design.
- The effects of shock and vibration can be reduced by a suitable packaging design for the goods.
- The effects of shock and vibration can be reduced with proper goods securing routines.
- The goods shock and vibration exposure can be reduced by modified handling routines.

Reduction of the shock and vibration exposure by modifying the carrier design

Shock and vibration on a railway goods carrier is caused by – wheel-rail interaction, – wagon-wagon interaction or the powertrain. In principle there are two possibilities to reduce the goods shock and vibration exposure by modified carrier design.

One possibility is to isolate the goods carrier from the generating regions. The transmission paths can be eliminated by for instance introducing or improving the

existing vibration isolation in the bogie. Another possibility is to use floating floor constructions for supporting the goods. Both these alternatives exist and are possible to introduce. It is important though that cheap solutions are developed in order to bring down the costs and make it possible to equip a substantial part of the carriers with these solutions.

Another alternative is to reduce the generation of shock and vibration. Tailoring the primary bogie suspension is one way of reducing the goods vibration due to wheel-rail interaction. Introducing automatic couplings may eliminate the longitudinal jerks caused by inadequately coupled wagons. These solutions also exist commercially but have to be made cheaper in order to become a realistic alternative on a substantial part of the carrier stock.

Modify product design

Products that are often damaged during transportation may be redesigned to improve the ability to resist shock and vibration. Vibration testing is a valuable tool for this purpose.

Packaging design

Many products are transported in packages that may be designed to protect the products from unwanted environmental factors such as moist or shock and vibration. Lots of goods damages can be avoided by proper packaging designs. A well designed package isolates the product from shock and vibration. A poorly designed packaging may cause goods damages. Consider for instance packages placed on top of each other. Each package must then be able to carry the weight of all packages above. If not, the whole pile of packages might collapse and drop to the carrier floor. Another well known example is that the risk for damages decrease with the degree of filling the package. Vibration testing is a valuable tool in packaging design.

Load securing routines

As explained above many goods damages are consequences of sliding cargo. Load securing routines aim to prevent cargo from sliding or moving relative to the carrier. For each transportation mode the load must be secured to resist certain dimensioning accelerations, see table 11. In physical terms the risk of sliding cargo is reduced by an increased friction force between the carrier and the cargo. This can be achieved for instance by using a carrier surface with a high friction coefficient or by strapping the cargo to the carrier. A more unusual solution is to insert obstacles on the carrier surface.

Handling routines

Improper handling causes the highest goods acceleration levels and is responsible for the major part of the goods damages. It is therefore important to find modified methods and routines that decrease the risk for goods damages.

It is for instance important to modify the switching routines so that wagons bumping into each other is avoided.

Loading and unloading routines must be modified to reduce the risk for dropping goods. Is it possible to replace truck handling with a more goods friendly handling system without losing flexibility?

Handling routines also includes goods responsibility issues. It is known that transport chains where it is clearly defined who is responsible for the goods have lower goods damage rates than other. This is an advantage for road transportation where the driver, which is sometimes the owner of the truck, feels a greater responsibility than in a large system like the railway transportation.

8.4.8 Goods monitoring

Goods monitoring refers to automatically and remotely surveying the goods condition. The goods condition may include any measurable entity, such as temperature, humidity, acceleration and position. Today it is becoming more and more common to provide the transportation with some kind of goods monitoring.

Many road transports are equipped with various “track and trace” systems allowing the transport to be tracked and traced by for instance its owner. There are also available on the market various measurement units and data-loggers for recording signals from sensors such as accelerometers, [21, 22]. SNAPSHOCK PLUS for example is a battery-powered series of acceleration recorders that registers peak acceleration events and the time of occurrence. Unfortunately there are still unsolved problems regarding the measurement of shock and vibration exposure, see section 4.5.4 above. There are other problems needing attention as well. For example, logistical and practical problems like who is taking care of the measurement system during the transport and when the destination is reached.

The possibility to monitor different aspects of the goods condition is not only a tool for collecting valuable information most important it is a valuable instrument to recover and strengthen the customer goodwill. Therefore no effort should be saved in the search for reliable goods monitoring methods.

8.4.9 Summary and recommendations for further research

The cost for goods damaged during transportation is for most companies unnecessary high. For this reason a high goods comfort to a reasonable price is one important component in a goods transportation system able to attract customers. Shock and vibration is the single most important cause of damaged goods and must be considered when goods comfort is discussed.

A comparison between railway, air and road transportation shows no drastic differences in goods shock and vibration levels. Negative for railway goods transportation is, however, the fact that the goods securing rules are more restrictive for railway transportation than for the other transportation systems.

The most important causes of goods damage during railway transportation are improper goods handling during loading, unloading and switching. Hence, it is an important task for further studies to develop improved handling routines that prevent goods damages.

Monitoring the comfort of sensitive goods is a method that would increase the competitiveness of the railway transportation system. A comfort monitoring system would improve the quality image of the transportation system. It would provide valuable knowledge on goods damage mechanisms and increase the possibilities to prevent damages. It would make it possible to make decisions on damage responsibility issues. Finally a comfort monitoring is likely to increase the comfort awareness in the whole transportation system.

Monitoring climate factors such as temperature is straight-forward. Shock and vibration monitoring require, however, a number of research tasks to be solved. The most important and probably most difficult of these is to find practical methods to measure accelerations representative for the goods shock and vibration exposure.

Another positive measure is to provide the customers with recommendations and advice regarding goods packaging. This will further improve the quality image and the customer confidence in the transportation system.

8.5 CONDITION MONITORING

Large sums are spent on maintaining the track and the running gear in a railway system. The costs for service and maintenance can be significantly reduced if the condition of sensitive parts in the system is regularly monitored. The idea is to detect a defect and take maintenance measures before it has consequences for other parts in the system. A wheel flat must, for instance, be detected and maintained before it has damaged the rail surface. A cracked wheel must be detected and maintained before a failure with potential derailment. A defective bearing must be detected and maintained before a failure that may damage a larger part of the bogie. The list of examples can be continued.

Techniques for condition monitoring of various kinds of elements exist but have to be improved and adapted for the specific application. Decisive for a large-scale implementation of these techniques in a railway system is of course the investment and operation costs compared to the savings in maintenance costs.

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