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# Prediction of Ground Vibration from Railways

Master of Science thesis,  
Department of Applied Acoustics,  
Chalmers University of Technology

## Abstract

Measured vibration levels from trains have been used to determine the distance dependence of ground – borne vibrations and a reference vibration level for each train type. Using the results of a Norwegian study, an empirical prediction formula has been made.

Field measurements were carried out at two sites in southwest Sweden. Three 3-directional accelerometers were used at three different distances from the middle of the railway track. All the accelerometers were mounted 50 cm below the ground surface. Each accelerometer for the three directional accelerometers was mounted to represent one direction. The signal generated due to the passing trains were recorded by a Digital Recorder (DAT). Due to the fact that this DAT has eight input channels and we used three 3-directional accelerometers, which means nine accelerometers, one channel had to be omitted.

MATLAB was used to analyse the signals. The vibration levels were analysed using time weighting S and the acceleration values were converted to velocity values. The measurements were carried out on three different types of trains: X2000, intercity, and freight trains.

Due to the limited number of measurements the prediction formula is only validated for a small speed range.

The work is a Master of Science thesis for the Department of Applied Acoustics, Chalmers University of Technology.

Key words: Vibration, ground, railway, train, propagation, measurement.

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## Preface

Far away from here, and thousands of years ago, in small places in the Arabian oasis, the first light of science was shined, many phenomena attracted the attention of people. Then, here and far away from that fantastic world, and in this time an idea appeared to study the ground – borne vibrations from railway traffic. This interesting subject, which I accepted the challenge to present as my thesis study for the M.Sc.degree in Acoustics.

The project presented in this Thesis was carried out at SP (Swedish National Testing and Research Institute). I would like to thank my supervisors at SP, Hans Jonasson and Jarl Olofsson for the wide knowledge they have and the very useful discussions that gave me more ideas about this project and more learning for the future life. I would also like to thank my professor and supervisor at Chalmers,(University of Technology), Dr. Wolfgang Kropp for his advice and the fruitful discussions, and best regards to Mikael Ögren for his help and the very useful discussions. Special wishes to the staff at SP, for helping me to finish this project and for the field owner were the field measurements were carried out.

I deeply dedicate this work to my family and my dearest friends, who have believed in me, encouraged me to finish this work.

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Sinan Al Suhairy

## Conclusions

The measurements results indicate that the most important vibration direction is the Z direction (vertical vibrations). It is clear that at 10m the vibration velocities have more or less the same values for the freight, intercity and X2000 trains. But far from the track, the vibrations of the freight trains have been attenuated less than for the other two trains; at 80m the vibration level is almost double for the freight trains compared with X2000 and the intercity trains.

For the results obtained for the exponential  $B$ , which is the distance dependence exponential, it was found that  $B$  has always the minus sign and that it has completely different values at the very close distance 10m than it has at the at far distances 40m and 80m respectively. This could be due to the effect of near field waves. At long distances the value of  $B$  changes due to the train type or train length.

The exponential  $B$  for the X2000 trains and intercity is large at long distances, which denotes that the generated vibrations suffer a lot of damping for the these trains, while for the freight train  $B$  it is less than for the others.

The fast trains, X2000, generate different spectra compared to those of the freight trains, which could be due to the two different speeds and lengths. Most of the frequencies generated by the freight trains are within the low frequency ranges while for the X2000 the frequencies are within the high frequency range.

The explanation to this is that the ground attenuation is less because of more low frequencies, freight trains are heavier, slower, and longer trains than the others, that is more of a line source than of a point source.

According to these comparisons, and due to the fact that the low frequencies can propagate far from the source without suffering a significant attenuation in the ground, one can say that *slow, long and heavy trains generate more vibrations at low frequencies than the fast short trains. These vibrations do not suffer significant damping from the ground, so they can propagate further away from the source in the ground causing more disturbance to the urban. Most vibrations are produced by the freight trains.*

# 1 Introduction

## 1.1 Background

Since the earliest days of railways in urban areas, there have been complaints about house vibration caused by the passage of trains. In this paper we would like to consider the problem of vibration caused by traffic on surface railways, a subject that has big attention for the modern life.

The operation of modern railways has been attended in train weight, train speed and wagon axle load. At the same time great attention has been paid to track quality; the use of continuously welded rail is common, heavier rail sections and heavy concrete sleepers have been introduced together with deeper ballast, whilst regular mechanized maintenance of track line and level is the rule. Clearly, the change in vehicle and train requirements has been matched to some extent by developments in track design.

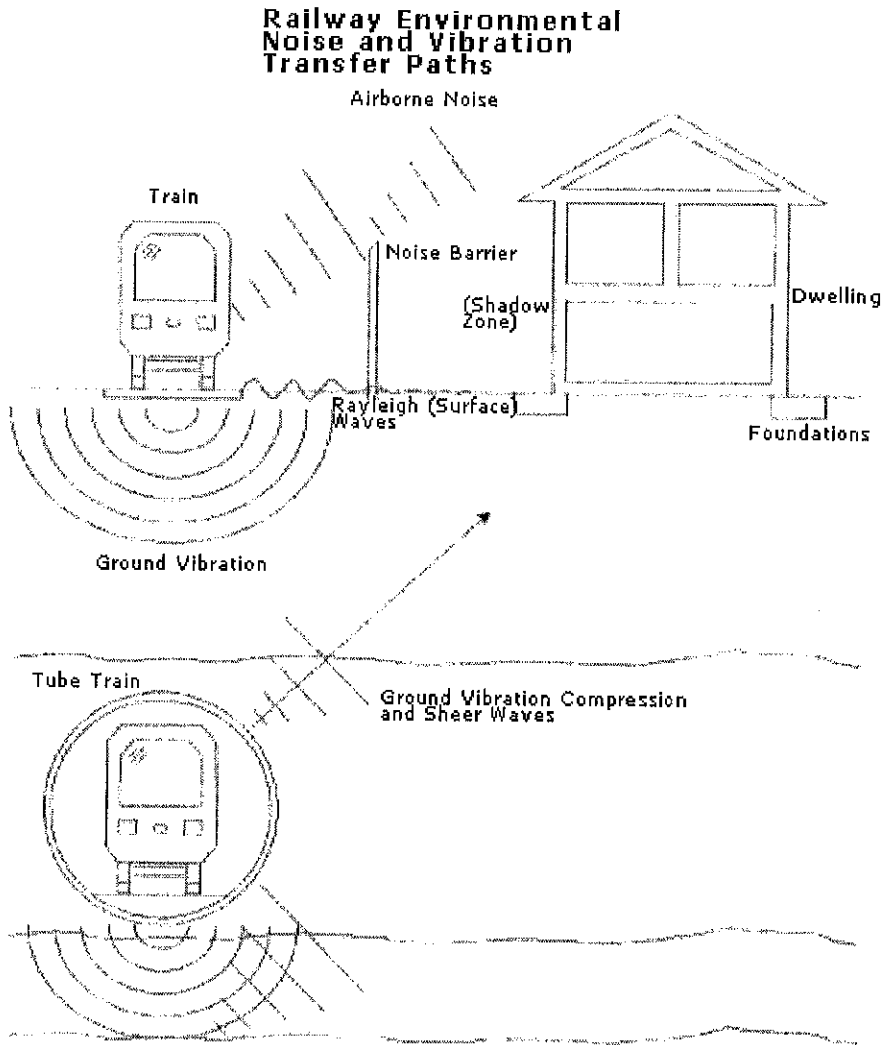
Larger problems appeared when people started to build and use the underground railways, which cause a bigger problem for ground vibrations; a full discussion of this subject was covered by paper [1]. A moving train creates a moving force pattern on the ground. The nature of this force pattern is modified by the elements between the train and ground, the rail, the rail supports, the sleepers or continuous slab, the ballast etc. The force gives rise to propagating waves within the ground and a number of types of wave can exist. For surface railway lines it is usual for a form of waves known as Rayleigh (see chapter 4.2.2) waves to dominate propagation to a distance.

Rayleigh waves can have relatively slow speed in the ground and long wavelengths – many meters – dependant on ground conditions. These properties give rise to particular problems. In some circumstances – high train speeds and soft ground – it is possible for trains to travel faster than the speed of Rayleigh waves in the ground. A phenomenon analogous to an aircraft supersonic bang then occurs, with very large increases in ground vibration level occurring for small increases in train speed. This phenomenon has been reported from a site in south – west Sweden when the X2000 high-speed train was introduced. Rayleigh wave speeds in the ground at the site were estimated to be about 160km/h. Train speeds changed from 140 km/h to 180 km/h with a resultant ten-fold increase in ground vibration levels. This gave rise to severe disturbance to buildings in the near vicinity of the railway.

In situations where very long wavelengths predominate, usually associated with heavy freight trains, control of vibration is very difficult. Mitigation measures, which are of benefit for shorter wavelengths, for example creating discontinuities in the ground or using piled foundation for buildings, are less effective. Vibration from trains manifests itself in two main ways. In some situations people can feel it and the effect can be exacerbated by floor resonances within a building. Secondary effects include noise radiation and disturbance of fixture and fittings.

Many parameters affect train vibration and propagation. Heavy freight trains do give rise to specific problems, particularly when the wagon suspension system employs friction damping as such dampers can "lock". If this occurs, the effective unsprung masses are high and vibration generation is efficient. Frequencies of vibration are low, between 0,5 – 100 Hz, and wavelengths in the ground long – tens of meters. Sites exist where vibration can be felt in the ground at over a hundred meters from the railway and the sensation is dramatically enhanced in a car whose own suspension amplifies the ground motion! [3]

Passenger trains and underground trains tend to give rise to higher frequency vibration. This is often perceived as a rumble in buildings close to tube lines, for example. Perceptible vibration can however still be produced if the building, usually the floors, exhibits a resonant response. A particular feature of trains tending to give rise to higher vibration is that of axle-hung traction motors. Again the relatively high-unsprung mass is to blame.



**Figure 1.1** Vibration generates by the railway and propagates to the urban area.

## 1.2 Literature review

Big attention has been paid to the ground vibration from railway traffic, many studies and researches were carried out for this purpose. In this chapter we will review some previous studies that have been made. Regarding to the wave propagation in the ground, which has been studied in many researches, such as Ewing (1957), who discussed the wave propagation in elastic media, different types of sources, like line and point source, depending on the source generator (load). Deeper studies have been made, Richart (1970), talks about the interaction between the surrounding soil and the rigid body for the heavy sleepers. More studies were carried by Aki and Richards (1980), Kaliski (1992) and Kramar(1996). According to the ground vibrations from railways, one important question was here raised, should the train be considered as a point or a line source. Studies regarding the trains as line source were carried out by, Verhas (1979), Chua

(1992), and Hunt (1994). On the other hand other researches have been made regarding the train as point source, Verhas (1979) as well. An idea of an array of point sources has been investigated by Fujikakae (1986), and Ford (1987). Krylov and Ferguson (1994) present a theoretical model of the excitation mechanism of ground vibrations generated by trains. The model was based on theoretical properties of the rail and train and ground parameter. This topic was solved by Green's function. Volberg, he is one of the researchers who has carried out measurements of railway included ground vibrations at different locations, his results showed that the ground vibrations are excited weaker in rock than in clay, the vibrations are more attenuated in clay soil than in rock. The author's final conclusion was, that the ground vibration generated by trains is relatively connected to the ground type and properties. Kjörling (1995) has measured the ground vibration from fast trains, and his measurements show that high – speed trains and freight trains generate different kinds of frequency spectra, faster and slower trains produce higher and lower frequencies, respectively. Madshus (1996) illustrates a special model (empiric), to predict low frequency vibration from fast trains. This model was based on three main parameters, the speed factor, distance factor and the type of the train. The model was expanded by adding the ground response factors and the house response parameters. Lang (1988) studied the ground vibration according to different types of tracks. Regarding to building response for the ground vibrations produced by passing trains, many researches have been made for this purpose. Waves propagation in ground – structure systems discussed by Takahashi (1985). He considered a two dimensional visco elastic half space (VEHS) and structure with ground contact at two places, the source is a harmonic line load on the surface of the VEHS. Seglo (1975), Lysmer(1978) and Anglov (1985), described FEM connection with the wave propagation in elastic media. As well as Zienkiewicz (1979) and Huges (1987).

## 2 Vibration Generation by Trains

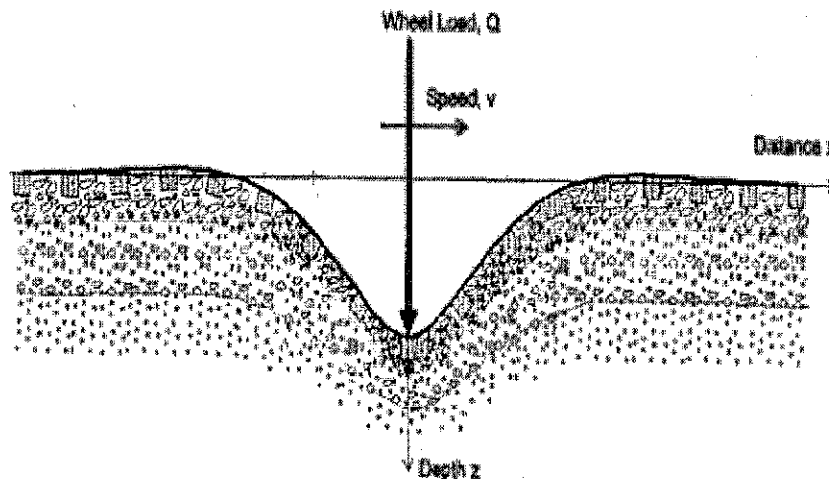
### 2.1 General

It is clear that when a train stands on the track, a stress pattern is produced in the ground beneath and around the train, which is sufficient to support the train (or any other vehicle), figure 2.1. When the train moves the stress pattern will move with it, although modified to a small extent by the finite propagation velocity of the stress waves. This moving stress pattern must impress stress waves into the surrounding ground even in the absence of any imperfections or periodic irregularities in the vehicle or the track. Whether this basic moving stress pattern generates a sufficient response in the surrounding soil property is unknown, but their particular geological conditions in which this might happen. See [29].

Obviously the particular railway has many features, which are capable of supplementing the basic stress field beneath the train. Any unsteady riding of the vehicle such as bouncing, rolling, pitching and yawing must result in additional fluctuating forces on the track structure. Recognized defects such as eccentric wheels, unbalanced wheels and wheel flats may also contribute to ground disturbance. The track itself does not provide uniform support; the rails, themselves of fixed length, are supported on sleepers placed at regular intervals, and the sleepers are in turn surrounded by and resting upon stone ballast. This ballast bed may by very nature provide a somewhat variable support, and void age below the occasional sleeper is a well-known fault.

All of these track features can be expected to contribute to the stress field present in the ground below and beside the train, and hence contributed to the vibration disturbances, which propagate to the surrounding soil. Clearly some of these will produce a purely local effect in the case of isolated features, whilst others will provide a regular pattern moving with the train.

The extent to which these features promote vibration can be expected to depend on the speed of the train and the weights of the vehicles within it. The static weight of the train provides the basic stress field due to the train, whilst the unsprung masses and the suspension characteristics of the vehicles, associated with their speed, will determine the extent to which track and rolling stock characteristics enhance this stress field.

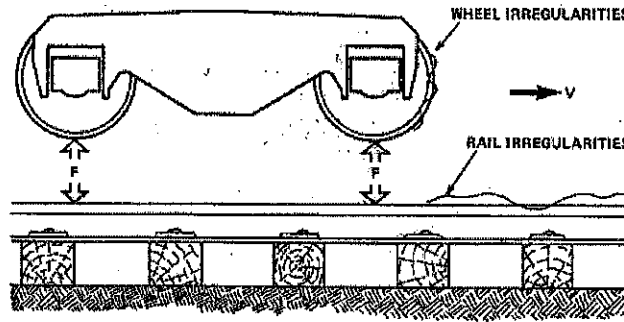


**Figure 2.1** The wave pattern moving with the train direction. [29]

## 2.2 The Ground – Vibration Generating Factors

### 2.2.1 Train/Track Interaction

It is believed that as the train proceeds down the track, dynamic forces arise between the wheel and the rail due to irregularities of the surface and wheel, as in figure 2.2, and possibly to irregularities in the support structure beneath the rail.



**Figure 2.2** Train /track interaction

The rail response velocity,  $V_R$ , can be shown to be proportional to the wheel,  $Z_W(\omega)$ , and the rail,  $Z_R(\omega)$ , impedances according to the following equation:-

$$V_R \propto \frac{Z_W(\omega)}{Z_W(\omega) + Z_R(\omega)} \quad (2.1)$$

Rail roughness is taken to mean the profile irregularities on the rail such as might be measured by a track geometry car; and wheel roughness refers to the out – of – roundness of the wheel, due to wheel flats, for example.  $Z_W(\omega)$ , and  $Z_R(\omega)$  are the vertical point impedances of the wheel and the rail respectively, i.e. the amplitude and the phase of the force required to generate a unit velocity at frequency  $\omega$ . It should be noted that  $Z_W(\omega)$  is not just the impedance of the wheel but includes the influence of the axle, the bogie, the car body, and bogie suspension elements. The most efficient impedance will be the wheel impedance  $Z_W(\omega)$ .

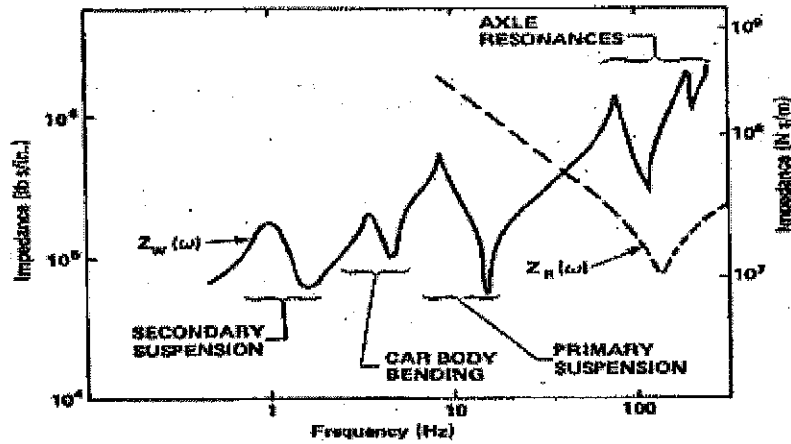


Figure 2.3  $Z_w$  and  $Z_R$  for a typical transit car operating on typical tie and ballast rail.

Figure 2.3 shows an order of magnitude representation of  $Z_w$  and  $Z_R$  for a typical transit car operating on typical ballast rail. Resonances below 10 Hz associated with the secondary suspension (between the car body and bogie) and the first car body bending mode are generally of no interest since ground vibration levels below 10 Hz are usually too small to be of any concern. The reason that ground vibration levels are so low at very low frequencies is illustrated clearly in figure 2.3. For frequencies less than about 5 Hz,  $Z_w$  is so much less than  $Z_R$  that the rail simply does not respond. Consequently, in this frequency region it can be reasonably assumed that when the wheel encounters an irregularity it moves up and over the irregularity and the rail remains essentially stationary.

Between 10 Hz and 30 Hz the vehicle impedance  $Z_w$  and rail impedance become more comparable in value although  $Z_w$  is still less than  $Z_R$ . The primary suspension resonances that usually occur in this frequency range can have significant effect on ground vibration. See [2]. To see why, note that below 30 Hz in the figure 1.3,  $Z_R \gg Z_w$  and, consequently, from equation 1.1.

$$V_R \propto \frac{Z_w}{Z_R} \quad (2.2)$$

Equation (2.2) shows that if  $Z_w$  is made larger than the rail, due to some design change to the bogie, the ground will respond more. The rail vehicle impedance  $Z_w$  in figure 2.3, between the peak below 10 Hz and the trough above 10 Hz is controlled by the primary suspension stiffness. Increasing that stiffness increases  $Z_w$  and, as Equation 2.2 shows, that increasing  $Z_w$  will increase ground vibration. This phenomenon is not speculative and has, in fact, been observed in field measurements [2].

In the same figure above one can observe another phenomenon from measurements of train generated ground vibration i.e., the peak in ground vibration spectra at around 40 Hz where the rail and vehicle impedance are equal that  $Z_R$  is spring like and  $Z_w$  is mass like. Consequently,  $Z_w$  and  $Z_R$  are of opposite sign, and the denominator of Equation 2.1,  $Z_R \pm Z_w$ , is nearly zero. This is essentially a resonant phenomenon in which the equivalent wheel – gearbox – axle – propulsion motor mass, i.e. the unsprung mass, is resonating on the rail foundation stiffness, resulting in an amplification of ground vibration.

Above 50 Hz in the same figure,  $Z_w \gg Z_R$  and even though there may be an axle resonance in the frequency region. Equation 2.1 shows that the rail response and ground vibration are independent of either the wheel or rail impedance.

### 2.2.2 Wheel/Rail Excitation

As mentioned above, one of the excitation mechanisms for ground vibration is the irregularities on the surface of the wheel and rail. If we are interested in train speeds from 30 to 110 km/h and frequencies of 10 – 250 Hz, then the irregularities with the wavelengths from 35 mm to 3 m are of primary interest. For the wheel the irregularities of greatest importance are flat spots, which are generated when the wheel slides during the braking. A full study is available in [3] and [4].

### 2.2.3 Ground Response

In the following we will consider a train moving with speed  $v$  on a welded track with sleeper periodicity  $d$ . The quasistatic pressure mechanism of excitation results from load forces applied to the track from each wheel axle, causing downward deflection of the track. These deflections produce a wave – like motion along the track with speed  $v$  that results in a distribution of each axle load over all the sleepers, involved in the deflection distance. Each sleeper, in turn, acts as a vertical force applied to the ground during the time necessary for a deflection curve to pass through the sleeper. This results in generation of elastic ground vibration. Since, in the low – frequency band, the characteristics wavelengths of generated elastic waves are much larger than the sleeper dimensions, each sleeper can be considered as a point source. Calculating the vibration field radiated by a moving train requires the superposition of fields generated by each sleeper activated by all axles of all carriages, with the time and space difference between source (sleepers) being taken into account.

## **2.3 Ground –Borne Vibration For Different Trains Types**

For details on train characteristics please see Annex 3.

### **2.3.1 Steel Wheel Urban Rail Transit**

This classification includes both heavy rail transit and light rail transit. Heavy rail is generally defined as electrified rapid transit trains with dedicated guideway (*the type and the condition of the rails*), and light rail as electrified transit trains that don't require dedicated guideway.

Problems with ground – borne vibration and noise are common when there is less than 150 m between the railway track and building foundations. Whether the problem will be perceptible vibration or audible noise is strongly dependent on local geology and the structure details of the building. Complaints about ground – borne vibration from the surface track are more common than complaints about ground – borne noise. A significant percentage of complaints about both ground – borne vibration and noise can be attributed to the proximity of special rough corrugated track, or wheel flats.

### **2.3.2 Commuter and Inter City Passenger Trains**

This category includes passenger trains powered by either diesel or electric locomotives, in Sweden most of them are powered by electric locomotives. In terms of vibration effects at a single location, the major difference between commuter and inter city passenger trains is that the latter are on a less frequent schedule. Both often share track with freight trains, which have quite different vibration characteristics. The locomotives usually create the high vibration levels. There is the potential of vibration related problems anytime that new commuter or inter city passenger service is introduced in an urban or suburban area.

### **2.3.3 High Speed Passenger Trains**

High – speed passenger trains, such as the Japanese Shinkansen, the French TGV, the German ICE and the Swedish X2000, have a potential of creating high levels of levels of ground – borne vibration. Ground – borne vibration should be anticipated as one of the major environmental impacts of any high speed train located in an urban or suburban area.

### **2.3.4 Freight Trains**

Local and long distance freight trains are similar in that they are mostly electric – powered and have the same types of cars. They differ in they overall length, number and size of locomotives, and number of heavy loaded cars. Locomotives and rail cars with wheel flats are the sources of the highest vibration levels.

### **2.3.5 Automated Guideway Transit Systems (A G T)**

This transit mode encompasses a wide range of transportation vehicle providing local circulation in downtown areas, airports and theme parks. In general, ground – borne vibration can be expected to be generated by steel – wheel /steel – rail system even when limited in size. Because AGT systems normally operate at low speeds, have lightweight vehicles, and rarely operate in vibration sensitive area, ground – borne vibration problems are very rare.

### 3 Vibration propagation

#### 3.1 Background

Once a transient stress variation is produced in the ground below the track, it will propagate away from the track as ground – borne vibration. A variety of modes of vibration are possible within the ground, and the principal types are the following:

- (a) Compression waves, (longitudinal waves), with particle motion being an oscillation in the direction of propagation;
- (b) Shear waves; with particle motion being an oscillation in a plane normal to the direction of propagation;
- (c) Rayleigh waves, which are surface waves, with a particle motion generally elliptical in a vertical plane through the direction of propagation. (see chapter 3.2)

In the ideal case when the ground is homogenous the longitudinal and shear waves propagate in all directions away from the source, and hence suffer substantial geometric attenuation, as well as losses due to the damping properties of the ground. The Rayleigh waves, being surface waves, do not suffer the same geometric attenuation, but are still subject to loss by damping. In practice the ground is far from homogenous; it may well be stratified and posses discontinuities. In such a case additional modes of vibration can propagate along the interfaces of strata, and mode conversion from one type of wave to another may be encouraged.

The various modes have different propagation velocities. The compression waves travel at typically 1000 m/s, whilst the shear and Rayleigh waves are much slower. Velocities for these seem typically to be about 200 m/s, but Rayleigh waves have been reported as slow as 35 m/s, see [29].

The vibration energy is not shared equally among the modes. Because of different geometric attenuations, the Rayleigh wave carry most of the vibration energy at significant distances away from the track. Reference [6] suggests that the ground vibrations generated by the vertical oscillation of a flat plate on the ground, about two thirds of the total energy is carried by the Rayleigh waves. A further significant factor is that high frequencies are attenuated much more rapidly than low frequencies, so that low frequencies dominate the spectrum at distances of more than a few meters from the source.

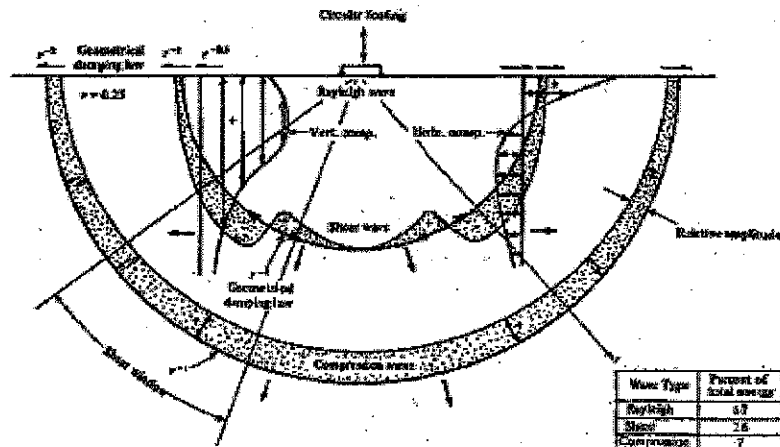


Figure 3.1 Wave propagation in the ground [29].

## 3.2 Wave Types

### 3.2.1 General

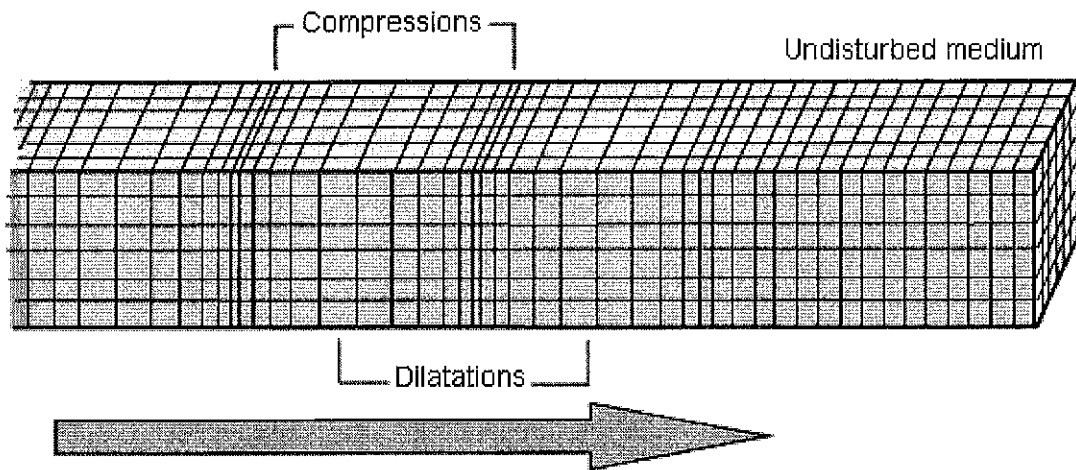
There are several different kinds of waves, (these waves are exactly acting as the Seismic Waves). All the generated waves move in different ways. The two main types of waves are **body waves** and **surface waves**. Body waves can travel through the earth's inner layers, but surface waves can only move along the surface of the planet like ripples on water. Trains radiate seismic energy as both body and surface waves.

### 3.2.2 Body Waves

#### 3.2.2.1 P Waves

The first kind of body wave is the **P wave** or **primary wave (Longitudinal waves)**. This is the fastest kind of ground wave. The P wave can move through solid rock and fluids, like water or the liquid layers of the earth. It pushes and pulls the rock it moves through just like sound waves push and pull the air. Have you ever heard a big clap of thunder and heard the windows rattle at the same time? The windows rattle because the sound waves were pushing and pulling on the window glass much like P waves push and pull on rock. Usually we only feel the bump and rattle of these waves.

### P Wave



*The arrow shows the direction that the wave is moving.*

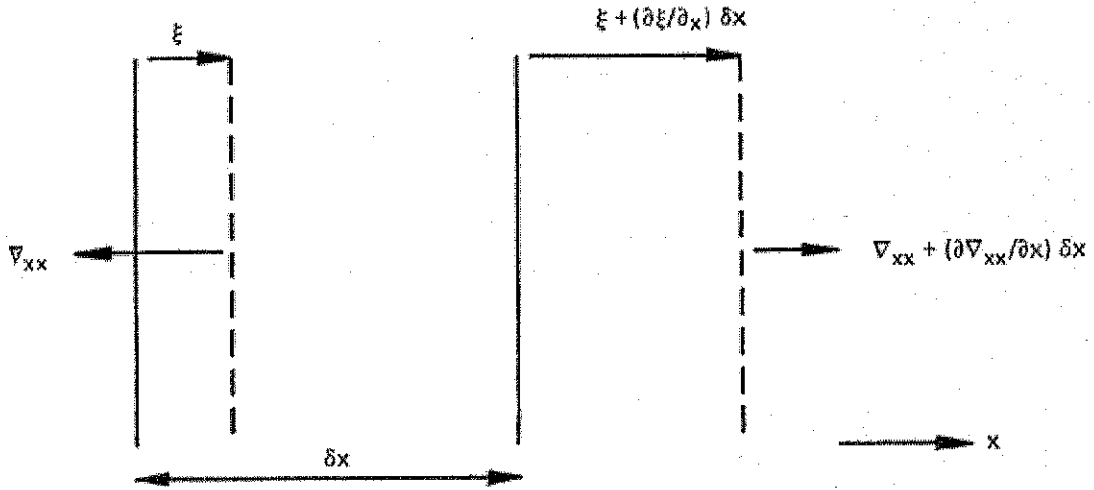
**Figure 3.2** Longitudinal waves.

In pure longitudinal wave motion the direction of particle displacement is purely in the direction of wave propagation; such waves can propagate in large volume of solids. Two parallel planes in an undisturbed solid elastic medium, which are separated by a small distance  $\delta_x$ , may be moved by different amounts during the passage of a longitudinal wave, as illustrated in the figure 3.2. Hence the element may undergo a strain  $\epsilon_{xx}$  given by

$$\epsilon_{xx} = \frac{\partial \xi}{\partial x} \quad (3.1)$$

The longitudinal stress  $\sigma_{xx}$  is, according to Hook's law, proportional to  $\epsilon_{xx}$ .

When a one – dimensional pure longitudinal wave propagates in a solid medium, there can be no lateral strain, because all material elements move purely in the direction of propagation, figure 3.2. This constraint, applied mutually by adjacent elements, create lateral direct stresses in the same way a tightly fitting steel tube placed around a wooden rod create lateral compression stresses if a compressive longitudinal force were applied to the wood along its axis. In these cases the ratio  $\sigma_{xx} / \epsilon_{xx}$  is not equal to  $E$ , (Young's modulus), complete behaviour of a uniform elastic medium shows that the ratio of longitudinal stress to longitudinal strain when lateral strain is prevented, [41].



**Figure 3.3** Displacement from equilibrium and stresses in a pure longitudinal wave.

$$\sigma_{xx} = B \frac{\partial \xi}{\partial x} \quad (3.2)$$

where

$$B = \frac{E(1-\nu)}{(1+\nu)(1-2\nu)} \quad (3.3)$$

The resulting equation of motion of an element is

$$(\rho A \delta x) \frac{\partial^2 \xi}{\partial t^2} = \left[ \sigma_{xx} + \left( \frac{\partial \sigma_{xx}}{\partial x} \right) \delta x - \sigma_{xx} \right] A = \left( \frac{\partial \sigma_{xx}}{\partial x} \right) \delta x A \quad (3.4)$$

where  $\rho$  is the material mean density (the earth density). Equation 3.2, and 3.4 can be combined into the wave equation

$$\frac{\partial^2 \xi}{\partial x^2} = \left( \frac{\rho}{B} \right) \frac{\partial^2 \xi}{\partial t^2} \quad (3.5)$$

The general solution of equation (3.5), which is the same form as the one – dimensional acoustic wave equation, shows that the phase speed  $C_l$  is

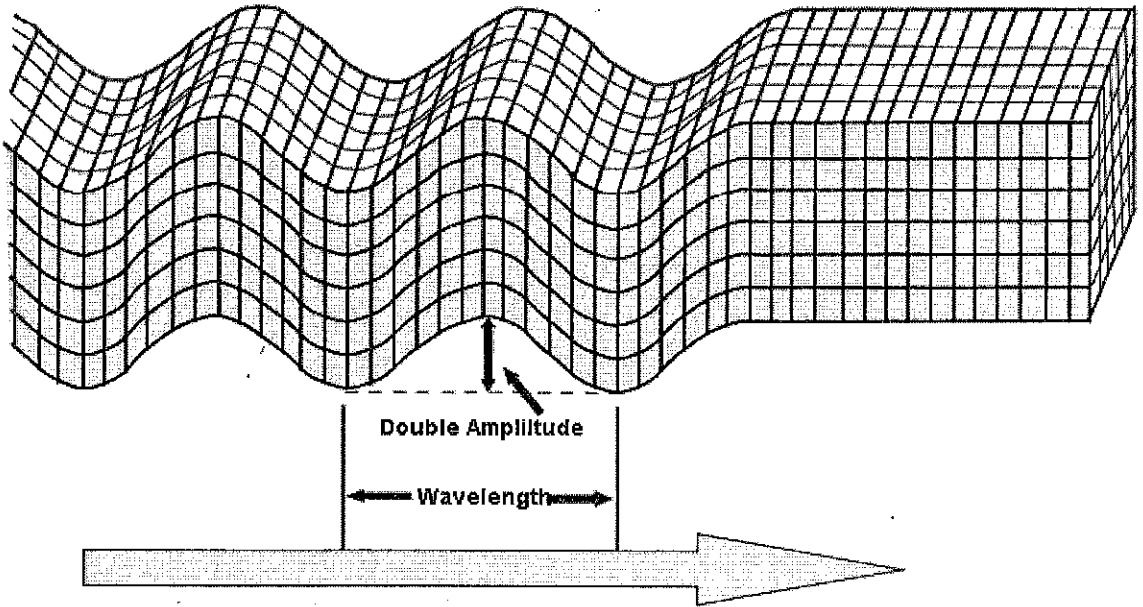
$$C_l = \left( \frac{B}{\rho} \right)^{1/2} \quad (3.6)$$

Which is independent of frequency, these waves are therefore non – dispersive.

### 3.2.2.2 S Waves

The second type of body wave is the **S wave** or **secondary wave (Shear waves)**, which is the second wave you could feel it generated by a passing train. An S wave is slower than a P wave and can only move through solid rock. This wave moves rock up and down, or side-to-side.

#### S Wave

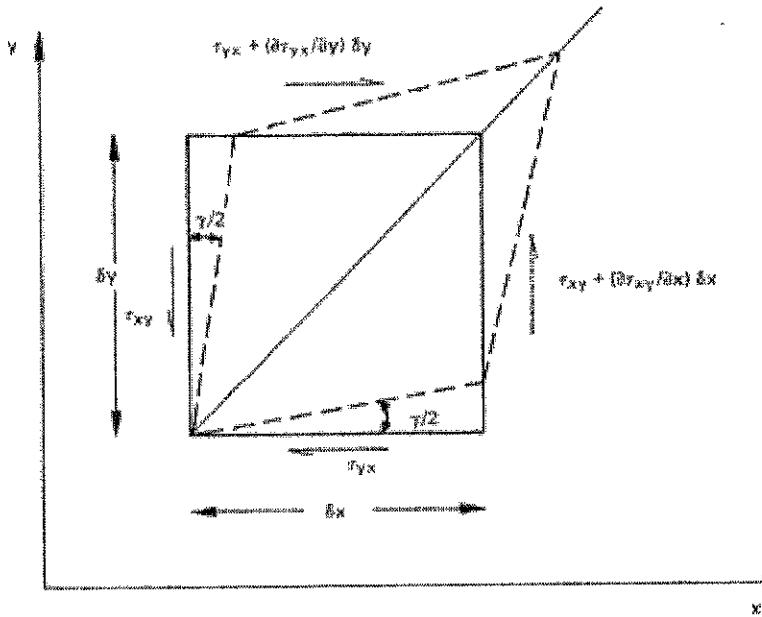


*The arrow shows the direction that the wave is moving.*

**Figure 3.4** Shear wave.

The shear modulus,  $G$  of a solid is defined as the ratio of the shear stress  $\tau$  to the shear strain,  $\gamma$ , shear deformation is represented in the figure 3.5. The shear modulus  $G$  is related to Young's modulus  $E$  by

$$G = \left( \frac{E}{2(1 + \nu)} \right) \quad (3.7)$$



**Figure 3.5** Pure shear strain and associated shear stresses.

In equilibrium and under pure shear, the shear stresses acting in a particular direction on the opposite faces of a rectangular element are equal and opposite, because the direct stresses on these faces are zero, i.e.

$$\frac{\partial \tau_{xy}}{\partial x} = \frac{\partial \tau_{yx}}{\partial y} = 0 \quad (3.8)$$

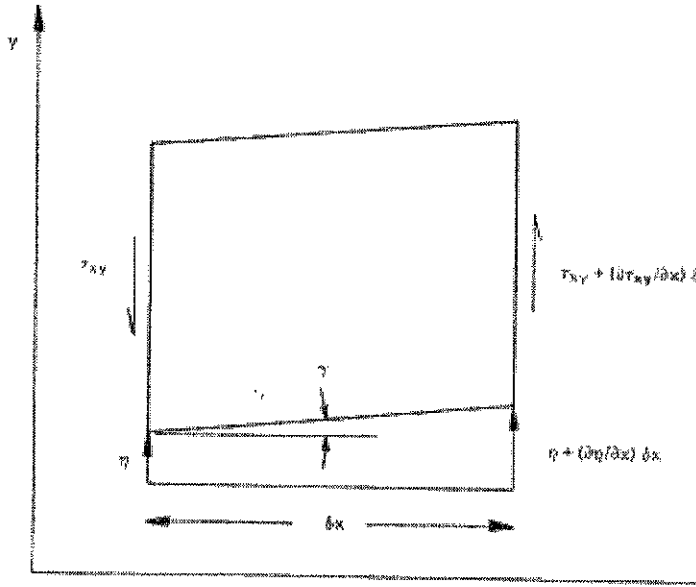
and

$$\tau_{xy} = \tau_{yx} \quad (3.9)$$

in figure 3.5.

In a dynamic situation this is not necessarily so; the difference in the vertical shear stresses causes the vertical acceleration  $\partial^2 \eta / \partial t^2$  of the element, see figure 3.6.

Consideration of the other equilibrium equations indicates that rotation of the element must also take place. The equation of transverse motion of an element having unit thickness in the  $z$  dimension is



**Figure 3.6** Displacement; shear strain, and transverse shear stress in pure transverse deformation.

$$\frac{\rho \delta x \delta y \partial^2 \eta}{\partial t^2} = \left( \frac{\partial \tau_{xy}}{\partial x} \right) \delta x \delta y \quad (3.10)$$

where  $\eta$  is the transverse displacement, and the stress – strain relation is

$$\tau_{xy} = G_y = \frac{G \partial \eta}{\partial x} \quad (3.11)$$

Hence the wave equation is

$$\frac{\partial^2 \eta}{\partial x^2} = \left( \frac{\rho}{G} \right)^{1/2} \frac{\partial^2 \eta}{\partial t^2} \quad (3.12)$$

The kinematics form of a shear wave is shown in figure 3.6. This takes the same form as the acoustics and longitudinal wave equations. The frequency – independent phase speed is

$$C_s = \left( \frac{G}{\rho} \right)^{1/2} = \left[ \frac{E}{2\rho(1+\nu)} \right]^{1/2} \quad (3.13)$$

The transverse shear wave speed  $C_t$  is seen to be smaller than the longitudinal waves speed,

$$\frac{C_t}{C_s} = \left[ \frac{1(1+\nu)}{2} \right]^{1/2} \quad (3.14)$$

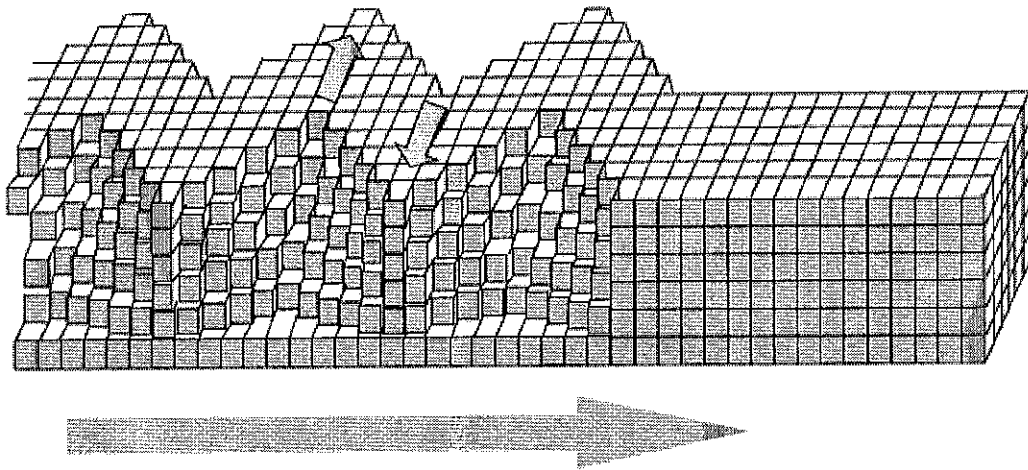
This ratio is about 0.6 for many structural materials. Such shear waves can propagate in large volume of solids (like the Earth).

### 3.2.3 Surface

#### 3.2.3.1 Love Waves

The first kind of surface wave is called a **Love wave**, named after A.E.H. Love, a British mathematician who worked out the mathematical model for this kind of wave in 1911. It is the fastest surface wave and moves the ground from side-to-side.

#### Love Wave



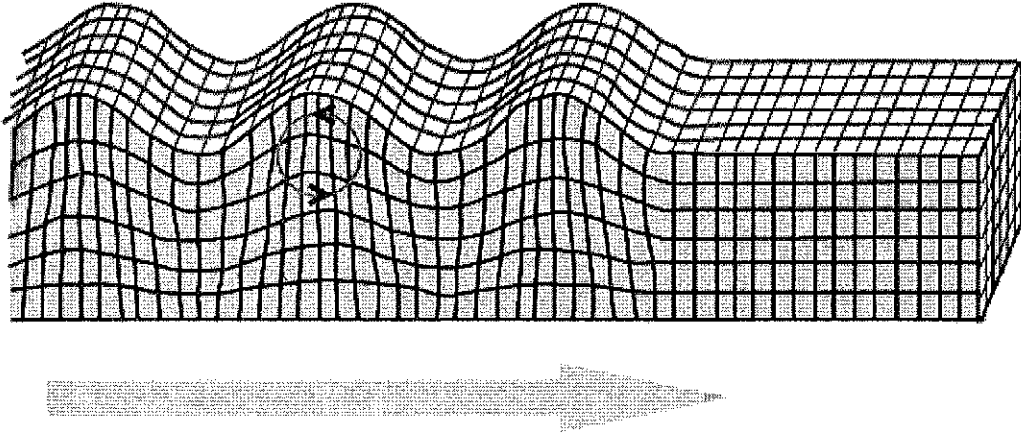
*The arrow shows the direction that the wave is moving.*

**Figure 3.7** Love wave.

#### 3.2.3.2 Rayleigh Waves

The other kind of surface wave is the **Rayleigh wave**, named for John William Strutt, Lord Rayleigh, who mathematically predicted the existence of this kind of wave in 1885. A Rayleigh wave rolls along the ground just like a wave rolls across a lake or an ocean. Because it rolls, it moves the ground up and down, and side-to-side in the same direction that the wave is moving. Most of the shaking felt from trains is due to the Rayleigh wave, which can be much larger than the other waves.

## Rayleigh Wave



*The arrow shows the direction that the wave is moving.*

**Figure 3.8** Rayleigh wave.

## **4 Effects of Ground – Borne Vibration**

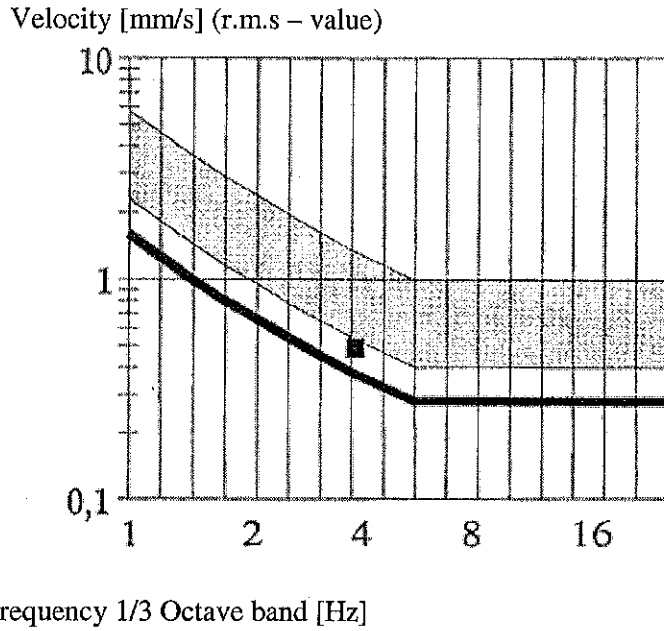
### **4.1 Types of Vibrations**

Whole-Body Vibration typically results from two types of forces acting on the operator. A non-cyclical force transmitted over a very short period of time, and for which the peak level is reached instantaneously is called a shock load. A vehicle striking an obstacle or a sudden drop into a hole may produce these shock loads. If these shock loads are sufficiently great, the operator may be thrown out of his seat or struck by objects flying around in the car. Less sudden forces are created by the vehicles regular motion over rough terrain. These are the most common motion-induced vibration forces that an operator encounters during his daily work. The effects of such forces vary with the duration of exposure. Thus they are more difficult to define than the instantaneous damage caused by high shock loads. Whole-body vibration considers these forces in combination and defines the effects of repetitive forces acting in a specific frequency range.

### **4.2 Frequency Range**

The frequency range of 0,5 Hz to 80 Hz, see [26], is significant in terms of the body's response. Every object (or mass) has a resonant frequency in somewhat the same sense that a pendulum has a natural frequency. When an object is vibrated at its resonance frequency, it will vibrate at maximum amplitude, which is larger than the amplitude of the original vibration. In the human body, individual body members and organs have their own resonant frequencies and do not vibrate as a single mass, with its own natural frequency. This causes amplification or attenuation of input vibrations by certain parts of the body due to their own resonant frequencies. The most effective excitation frequency for vertical vibration lies between 4 and 8 Hz. Vibrations between 2,5 and 5 Hz generate strong resonance in the vertebra of the neck and lumbar region with amplification of up to 240%. Between 4 and 6 Hz resonances are set up in the trunk with amplification of up to 200%. Vibrations between 20 and 30 Hz set up the strongest resonance between the head and shoulders with amplification of up to 350%. In a human body, this unwelcome situation may create chronic stresses and sometimes even permanent damage to the affected organs or body parts.

The ISO standards (*2631-1 and 2631-2, 1997*) propose a general guide on human response to building vibrations. This involves weighting curves of frequency response, which reflect the human response with respect to human annoyance. It can be seen in, figure 4.1, that, if vertical vibration in the velocity domain is considered, frequency components below 8 Hz are of great importance; thus, they have a high weighting factor.



**Figure 4.1** Weighting curves of frequency response.

To have an overview of the bandwidth spectrum for the ground vibration, which could be expected for a railway, one should look at the geometrical properties of the train in relation to its velocity. Typical dimensions are overall length of the car and axle distances. Axle distances of a car may vary between 2 m and 10 m. A train with a velocity of 25 m/s (90 km/h) may be expected to produce axle passage frequencies in the range of 2,5 Hz to 12,5 Hz [26]. If a typical railway wheel, having a diameter of 0,75 m to 1,0 m, with a single wheel flat is considered, the corresponding wheel flat occurrence frequencies may vary between approximately 8 Hz and 11 Hz. A railway wheel passing equidistant sleepers may generate what is often referred to as the sleeper passing frequency. For Swedish railways, where the nominal center – to – center distance of sleepers is 0,65 m, the corresponding sleeper passage frequency for a train with velocity of 25 m/s (90 km/h) becomes approximately 38,5 Hz.

Applying the equations below, the frequency ranges from the railways could be calculated.

- The sleeper passing frequency  $f_s$  can be found by, see [44]

$$f_s = \left( \frac{U}{l_s} \right) \text{Hz} \quad (4.1)$$

where  $U$  is the train speed in m/s and  $l_s$  the sleeper distance in m.

- The wheel passing frequency

$$f_A = \left( \frac{U}{a} \right) \text{Hz} \quad (4.2)$$

where  $a$  is the distance between two wheels in a bogie.

- Bending wave speed in rails

A good low frequency model for a rail is a beam on an elastic foundation. The bending wave speed is given by

$$C_{b,min} = \sqrt[4]{4s'B/m'^2} = \sqrt[4]{4\omega_0^2 B/m'} \quad (4.3)$$

this occurs at a frequency

$$\omega_{min} = \sqrt{2s'/m} = \sqrt{2}\omega_0 \quad (4.4)$$

$B$  is the bending stiffness of rail,  $B=6.4 \cdot 10^6 \text{ Nm}^2$  for UIC60, [See chapter 11].

$m'$  = mass per unit length of rail,  $m' = 60 + m_s/2l_s \text{ kg/m}$

$\omega_0$  = resonance radian frequency of the rail including the sleepers against the elastic foundation(ballast),

where  $f$  varied between 30 and 80 Hz,

$$\omega_0 = 2\pi f \quad (4.5)$$

$s'$  stiffness per unit length of elastic foundation.

$m_s$  mass for one sleeper

$l_s$  is the distance between two sleepers,  $l_s=0.6$

If we take the typical numbers like

$m_s=150 \text{ kg}$ ,  $\omega_0=50 \text{ Hz} \cdot 2\pi$ ,  $s'=18 \cdot 10^6 \text{ N/m}^2$  and put them into the equations we will get the minimum wave speed is approximately  $340 \text{ m/s} = 1224 \text{ Km/h}$  at 70Hz.

This value is much higher even if the elastic foundation were 20 times softer, the minimum wave speed would still be approximately  $160 \text{ m/s} = 576 \text{ km/h}$  thus for this type of motion, coincidence of train speed and wave speed is extremely unlikely.

The results from the equations above described that the frequencies generated by the railway traffic are within the response of the human body.

### 4.3 Type of Building and Receiver Location in Building

Since annoyance from ground – borne vibration and noise is an indoor phenomenon, the effects of the building structure on the vibration must be considered. Wood frame buildings, such as the typical residential structure, are more easily excited by ground vibration than heavier buildings. In contrast large masonry buildings with spread footing have a low response to ground vibration.

Vibration generally reduces in level as it propagates through a building. 1 to 2 decibel attenuation per floor is usually assumed. Counteracting this, resonances of the building structure, particularly the floors, will cause some amplification of the vibration. Consequently, for a wood – frame structure, the building – related adjustments nearly cancel out. The adjustments for the first floor assuming a basement are: -5 dB for the coupling loss; -2 dB for the propagation from the basement to the first floor; and +6 dB for the floor amplification. The total adjustments are -1 decibel. See [2]

## 4.4 The Response of the Building

The vibration caused in buildings by passing trains can be due to both ground – borne vibration and to air borne noise. Examples of both mechanisms can be identified, and both may occur in some cases. Where both mechanisms do occur their separation can be very complex. In this paper, however, we are concerned only with the behaviour of buildings when subject to ground – borne vibration; if building vibration does occur, disturbance is the usual result, not damage. Building response depends on the elastic properties of the ground, the type and the depth of the foundation of the building, the design and the construction of the building, and even on the location of the furniture within the building. Those available modes of response, which are excited, will depend on the character of the disturbance passing through the ground, in particular the frequencies present, and their corresponding wavelengths. Obviously the frequency ( $f$ ) and wavelength ( $\lambda$ ) are connected by the propagation velocity ( $c$ ) (or velocities, if more than one mode is present to a significant extent) according to the equation

$$c = f * \lambda \quad (4.6)$$

It may be that the local propagation velocity plays an important role in determining whether or not significant disturbance is caused to a particular building.

If the wavelength of the disturbance is long compared with the width of the building then the input to the building will be purely translational. A similar result could be expected if an integer number of wavelengths matched the building width exactly. When the building

width corresponds to  $(n - \frac{1}{2})$  wavelengths, where  $n$  is an integer, swaying of the building

might be expected to result, which might be amplified by the natural sway frequency of the building. In practice, of course, a combination of effects would occur, and many modes of vibration would be available for excitation, including those involving distortion of the building shell.

The important point, which can be derived from this simple argument, however, is that if a building mode is to be excited, then the correct frequency must be present in the ground vibrations, but also wavelength in the ground must be properly matched to the building dimensions. For example, if a building were inclined to sway at a particular frequency, there would be no excitation by the ground vibrations containing that frequency if the wavelength were such that only a translational input was provided. See [2].

If it were assumed that the spectrum of ground vibration due to trains on a given track was reasonably constant, it seems reasonable to suggest that for a wayside building to respond, it would have the appropriate modal frequency(ies) available, be of the right size (and orientation), and the local propagation velocity in the ground would have to be correct. One of the features of ground – borne vibration is the erratic way in which it affects some buildings and not others. Perhaps the degree of matching required before the building responds could account for this.

## 5 General Factors Influencing the Ground – Borne Vibration

A large number of factors can influence the vibration level at the receiver position, which makes it difficult to estimate the ground – borne vibration. The purpose of this section is to give a general appreciation of which factors have significant effects on the levels of ground – borne vibration. Table (5.1) is a summary of some of the many factors that are known to have, or are suspected of having a significant influence on the levels of ground – borne vibration, see [36]. As indicated, the physical parameters of the transit facility, the geology, and receiving building all influence the vibration levels. The important physical parameters can be divided into the following four categories:

- **Operational and Vehicle Factors** – This category includes all of the parameters due to the vehicle and operation of the train. Factors such as high speed, stiff primary suspensions on the vehicle, and flat or worn wheels will increase the possibility of problems from ground – borne vibration.
- **Guideway** – The type and the condition of the rails, the type of guideway, the rail support system, and the mass and stiffness of the guideway structure will all have an influence on the level of ground – borne vibration. Jointed rail (full welded), worn rail, and wheel impacts at special track work can all cause substantial increase in the ground – borne vibration.
- **Geology** – soil conditions are known to have a strong influence on the levels of ground – borne vibration. Among the most important factors are the stiffness and internal damping of the soil and the depth to bedrock. Experiences with ground – borne vibration is that vibration propagation is more efficient in stiff clay soil, and shallow rock seems to concentrate the vibration energy close to the surface and can result in ground – borne vibration problem at large distances from the track. Factors such as layering of the soil and depth to water table can have significant effects on the propagation of ground – borne vibration.
- **Receiving building** – the receiving building is a key component in the evaluation of ground – borne vibration since ground – borne vibration problems occur almost exclusively inside the building. The train may be perceptible to people who are outdoors, but is very rare for outdoor vibration to cause complaints. The vibration levels inside a building are dependent on the vibration energy that reaches the building foundation, the coupling of the building foundation to the soil, and the propagation of the vibration through the building. The general line is that the heavier a building is, the lower the response will be to the incident vibration energy.

**Table 5.1** Summary of some of the many factors that are known to have, or are suspected of having a significant influence on the levels of ground – borne vibration, [36].

<b><i>Factors Related to Vibration Source</i></b>	
<b>Factors</b>	<b>Influence</b>
Vehicle Suspension	If the suspension is stiff in the vertical direction, the effective forces will be higher. On transit cars, only the primary suspension affects the vibration levels, the secondary suspension that supports the car body has no apparent effects.
Wheel Type and Condition	Normal resilient wheels on rail transit system are usually too stiff to provide significant vibration reduction. Wheel flats and general wheel roughness are the major cause of vibration from steel wheel/steel rail system.
Track/Roadway Surface	Rough track are often the cause of vibration problems. Maintaining a smooth surface will reduce vibration levels.
Track Support System	On rail systems, the track support system is one of the major components in determining the levels of ground – borne vibration. The highest vibration levels are created by track that is rigidly attached to a concrete tracked. The vibration levels are much lower when special vibration control track system such as resilient fasteners; ballast mats and floating slabs are used.
Speed	As intuitively expected, higher speeds result in higher vibration levels.
Transit Structure	The general rule – of – thumb is that the heavier the transit structure, the lower the vibration levels. The vibration levels from a lightweight bored tunnel will usually be higher than from a poured concrete box subway.
Depth of Vibration Source	There are significant differences in the vibration characteristics when the source is underground compared to at the ground surface.
<b><i>Factors Related to Vibration Path</i></b>	
<b>Factors</b>	<b>Influence</b>
Soil Type	It is generally expected that vibration levels will be higher in stiff clay type soils than loose soils.
Rock Layers	Vibration levels often seem to be high near the track when the depth to bedrock is 10 m or less. Subways founded in rock will result in lower vibration amplitudes close to the subway. Because of efficient propagation, the vibration level does not attenuate as rapidly in rock as it does in soil.
Soil Layering	Soil layering will have a substantial, but unpredictable, effect on the vibration levels since each stratum can have significantly different dynamic characteristics.
Depth of Water Table	The presence of the water table is often expected to have significant effect on ground – borne vibration, but evidence to date cannot be expressed with definite relationship.
Frost Depth	There is some indication that vibration propagation is more efficient when the ground is frozen.
<b><i>Factors Related to Vibration Receiver</i></b>	
<b>Factor</b>	<b>Influence</b>
Foundation Type	The general rule – of – thumb is that the heavier the building foundation, the greater the coupling loss as the vibration propagates from the ground into the building.
Building Construction	Since ground – borne vibration is almost always evaluated in terms of indoor receivers, the propagation of the vibration through the building must be considered. Each building has different characteristics relative to structure borne vibration. The general rule for this, is that the more massive a building is the lower the levels of ground – borne vibration will be.
Acoustical Absorption	The amount of acoustical absorption in the receiver room affects the levels of ground – borne vibration.

## 6 Field Measurements

### 6.1 Test Sites

The data for this study “Prediction of Ground Vibration from Railways” are collected from measurements at two different sites (outdoor measurements), covering soft to medium stiff soil conditions. The first one is a spot between Alingsås and Algitsgården, figure 6.1. The ground quality for this site is soft clay, which is used for farming purposes. The second site was a small community, Torp figure 6.2. The ground here was a bit stiffer than at the first site. At each site, the vibration has been measured simultaneously at 8 points on the ground surface in the propagation area.

The problem of measuring ground borne – vibration induced by train is complicated by the fact that a small number of measurements can produce a very large amount of data; and processing all the data is not an easy task. The processing of data from acquisition, analysis and storage has been greatly improved in the last few years with the computer and science revolution, the computer capacity and software have improved. It is now possible to acquire, analyse and store more data than ever before. As this process continues, possibilities of increasing the understanding of the problem grow steadily.

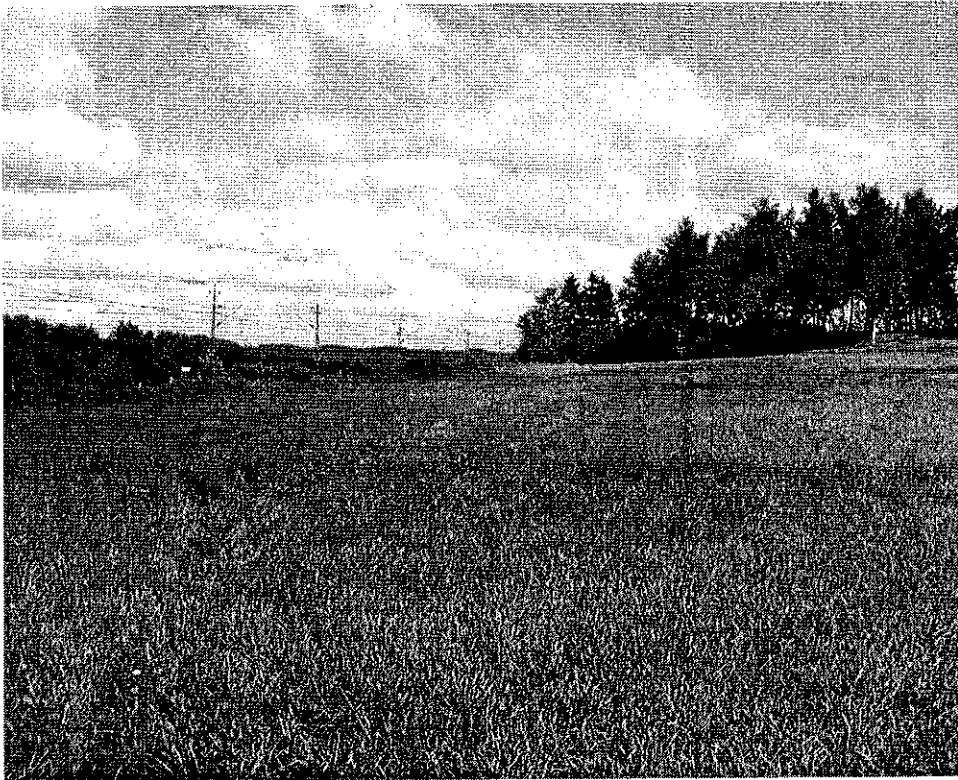


Figure 6.1 The location of the first field measurement.

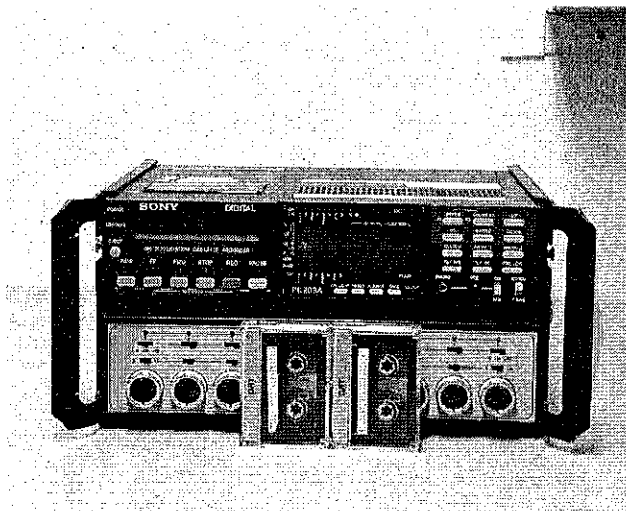


**Figure 6.2** The location of the second field measurement at Torp.

## 6.2 Field Equipment Set Up

The field measurements were carried out with co-operation of SP (Sveriges Provnings- och Forskningsinstitut), all the instruments were provided by this company. To measure the ground vibration from railways we needed several different instruments that can perform this kind of measurements.

- Sony Digital Recorder with 8 channels input. Figure 6.3.



**Figure 6.3** Digital Recorder.

- Three power amplifiers. Figure 6.4.

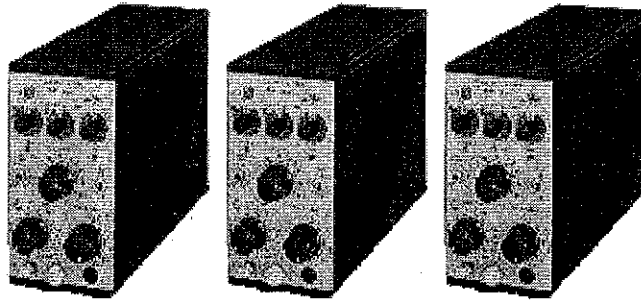


Figure 6.4 Power amplifiers.

- IPC system.
- Three directional accelerometer mounted in a closed box and water proofed up to 50m under the sea level. Figure 6.5.

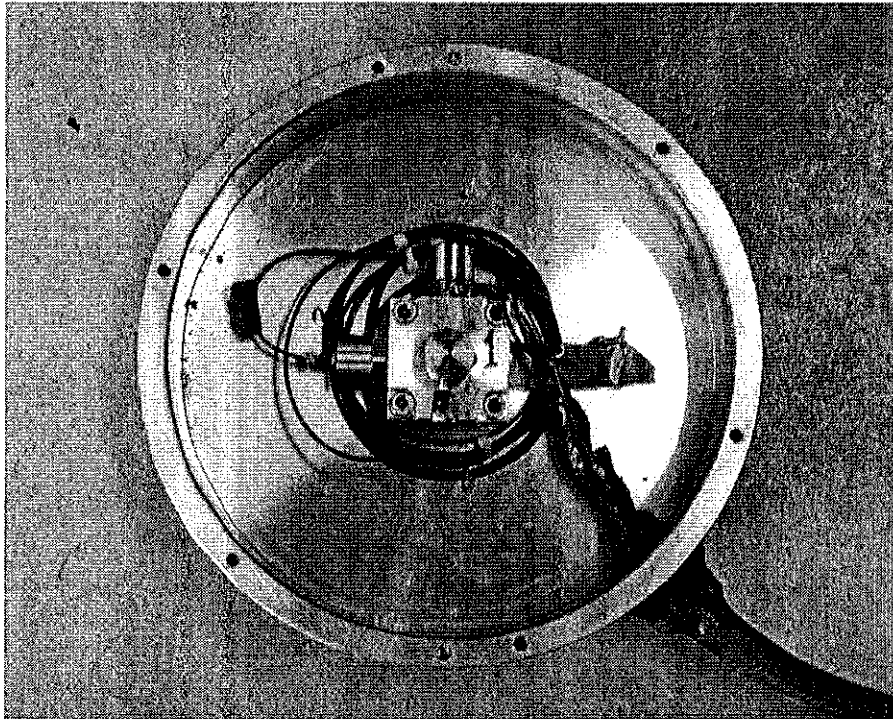


Figure 6.5 Three directional accelerometer mounted inside a waterproof box.

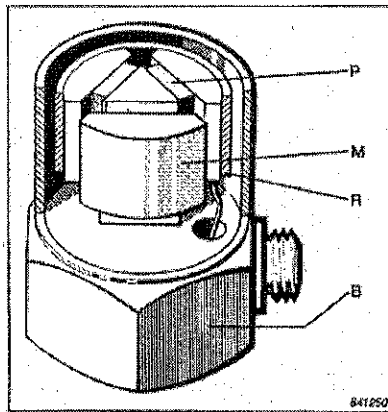
Accelerometers can be described as two transducers -- the primary transducer, typically a single-degree-of-freedom vibrating mass, which converts the acceleration into a force, and a secondary transducer, which converts the force of the seismic mass into an electric signal. Most accelerometers use a piezoelectric element as a secondary transducer. Piezoelectric devices, when subjected to a strain, output a voltage proportional to the strain. Note that piezoelectric elements cannot provide a signal under static (e.g., constant acceleration) conditions.

Important characteristics of accelerometers include range of acceleration, frequency response, transverse sensitivity (i.e. sensitivity to motion in the non-active direction), mounting errors, temperature and acoustic noise sensitivity, and mass. High-frequency-response accelerometers are used mostly for vibration and shock testing. Shock testing includes automobile and aircraft crash testing, and studying the effects of explosions or

earthquakes on buildings and other large structures. We used these accelerometers to measure the very low frequencies, between 4 – 80 Hz, from the ground vibration produced by the railway traffic.

### ***Piezoelectric***

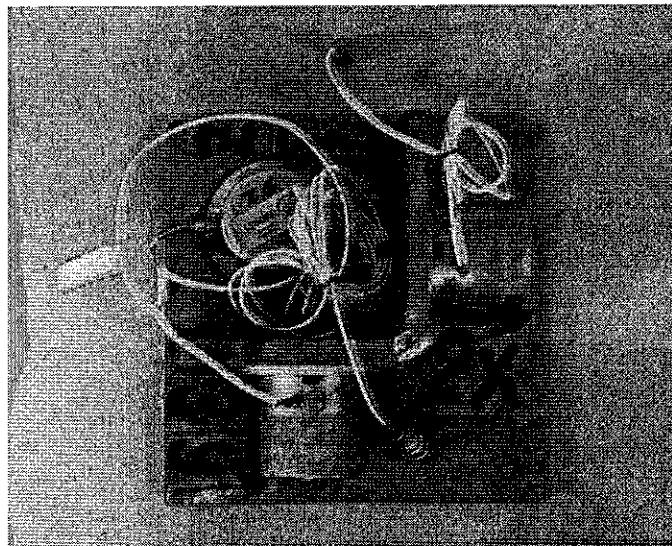
Piezoelectric transducers, figure 6.6, are often used in vibration-sensing accelerometers, and sometimes in shock-sensing devices. The piezoelectric crystals (often quartz or ceramic) produce an electric charge when a force is exerted by the seismic mass under some acceleration. The quartz plates (two or more) are preloaded so that a positive or negative change in the applied force on the crystals results in a change in the electric charge. Although the sensitivity of piezoelectric accelerometers is relatively low compared with other types of accelerometers, they have the highest range (up to 100,000 g's) and frequency response (over 20 kHz). But they are less efficient at low frequencies.



**Figure 6.6** Piezoelectric accelerometer, *(the unique Bruel & Kjaer, Delta shear design).*

*M= Seismic Mass, P=Piezoelectric Element, B=Base, R= Clamping Ring.*

- Two, three directional accelerometers each of them consisting of three separate accelerometers and these are mounted on a base made especially for them. Figure 6.7.



**Figure 6.7** Three directional accelerometers

- Cables.
- YAMAHA Electrical generator.
- Sony Video camera.
- Olympus Digital camera.
- Laser gun for speed measurements.

All the accelerometers were mounted 50 cm under ground [48] (*when vibration is be measured in the ground, it is recommended to place the accelerometers in a small hole, about 30-50 cm below the surface, experience has shown that the most stable results are achieved this way*).

The 3-directional accelerometers were mounted in three different directions (X, Y, and Z), where the X direction is parallel to the railway track, the accelerometer in the Y direction is perpendicular to the railway track, and the accelerometer in the Z direction is vertical. Each direction represents one channel and these channels are connected to the Sony digital recorder through the amplifiers.

Due to the Sony digital recorder, which has only 8 channels input, we had to omit one channel and that means one direction. We omitted the channel with the weakest input signal because we cannot get a lot of information from this signal. The channel was selected after analyses and comparison between the signals from all the channels. The field measurements have been made for more than 120 different trains at different distances as well as positions and locations.

The field measurements connection are shown in figure 6.8.

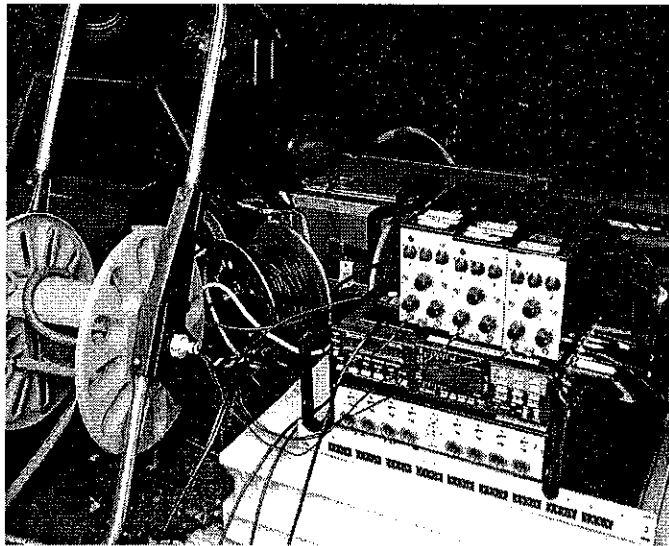


Figure 6.8 Field measurements set-up.

## 7 Analyses and Some Introductory Results

### 7.1 General

In an attempt to throw some light on ground vibration it is of interest to analyse some measurements, which we have carried out from the field in different sites in west Sweden. Measurements were made at four different distances, in three directions and for different types of trains.

The data for this project, which are obtained from the field measurements, cover at least the frequency range from 2 to 500 Hz but some of the measurements suffered from too high background noise at the low frequencies below 4 Hz. To acquire some statistical quantification, vibration from several trains, usually more than five, of different categories have been measured at each site. Based on the recorded time histories, one-third-octave band and frequency weighted r.m.s values according to ISO 2631 and ISO 8041, with slow time weighting  $S$  (1 s), have been determined. According to the previous studies and the results and our experience, the vertical  $Z$  direction is the most dominating direction compared with the others directions ( $X$  and  $Y$ ).

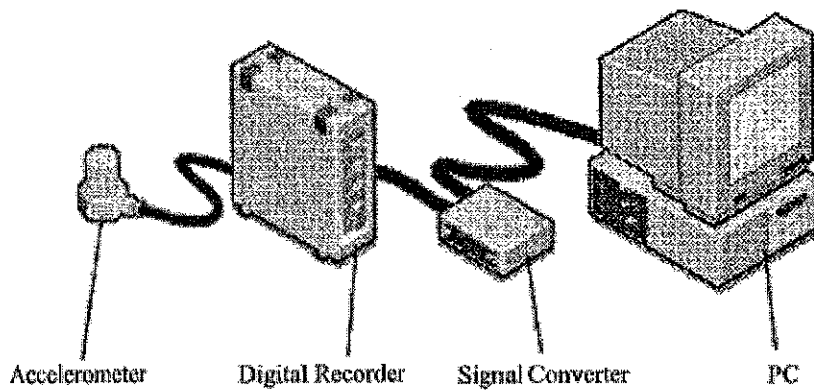
As a first step for analysing the results, the time history for all the trains were recorded digitally for 8 channels simultaneously using the programme Sony PC scan.

By analysing the time history for most of the trains, the acceleration [dB] against the 1/3 oct. band frequency was obtained as a first step, and we are interested also in the velocity against time in the 1/3 octave band, which will be analysed later on in this project. The analysis will be made for most of the trains to get a clear picture about the vibration generation and to be able to predict it against the human and building response. The figures 7.3, 7.5 and 7.7 below illustrate the  $Z$  – channel measured through the accelerometers for different types of trains and 20 m from the railway. The reference for the [dB] calculations, is  $10^{-6}$  [ $m/s^2$ ] for the acceleration, and for the velocity it is  $10^{-9}$  [ $m/s$ ].

### 7.2 Data Recording and Digitisation

First of all, the signal from the accelerometers was recorded by using a digital recorder “SONY Digital Recorder”, see chapter 6.2. To convert the analogue signal to a digital signal, which will be used for the further analysis, a computer programme called “Sony PC scan” was used, see figure 7.1, [29]. To get the information from the signal to the computer by the PC scan programme, the digital Recorder was connected to the computer through “Black Box”, a Signal Converter that belongs to the programme. By playing back the original signal by the Digital Recorder, all the channels were recorded as digital signals in the computer. From the time history and as a first step for analysing, MATLAB was used for obtaining all the information we need ended by the final results that illustrated as Velocity [mm/s] for each octave band.

Annex 2 shows MATLAB programs for calculating the 1/3 oct. band and for calculating the vibration velocity [ $mm/s$ ] for the measured trains. By reading the MATLAB part (1) programme and applying it, one can get, acceleration [dB], acceleration [ $mm/s^2$ ], velocity [mm/s] and velocity [dB]. All these values have been analysed in the 1/3 Oct. band according to the programme MATLAB part(2), which is connected to MATLAB part(1).

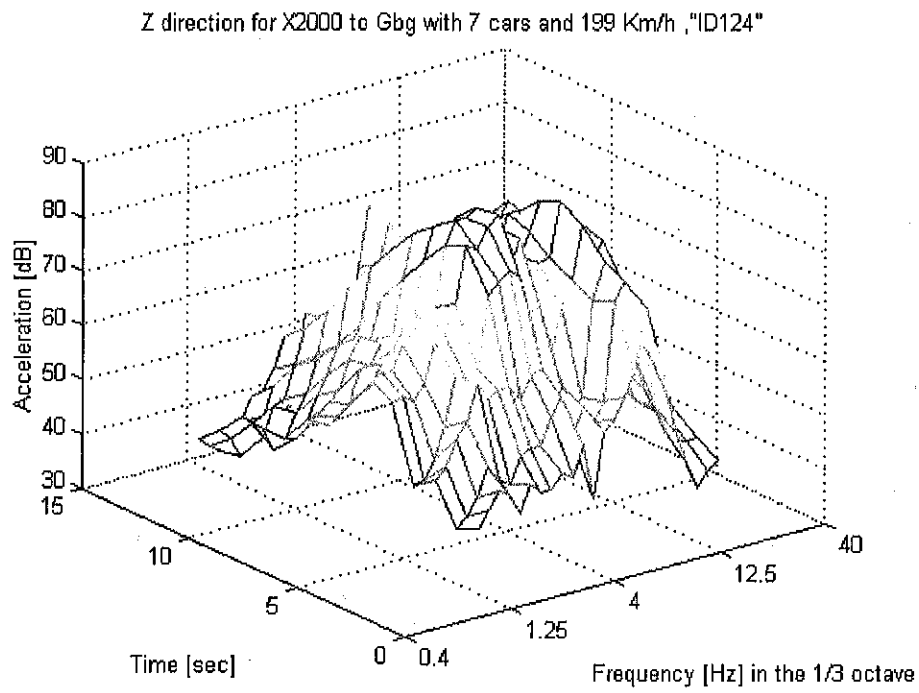


**Figure 7.1** Connection to convert the analogue signal to digital signal

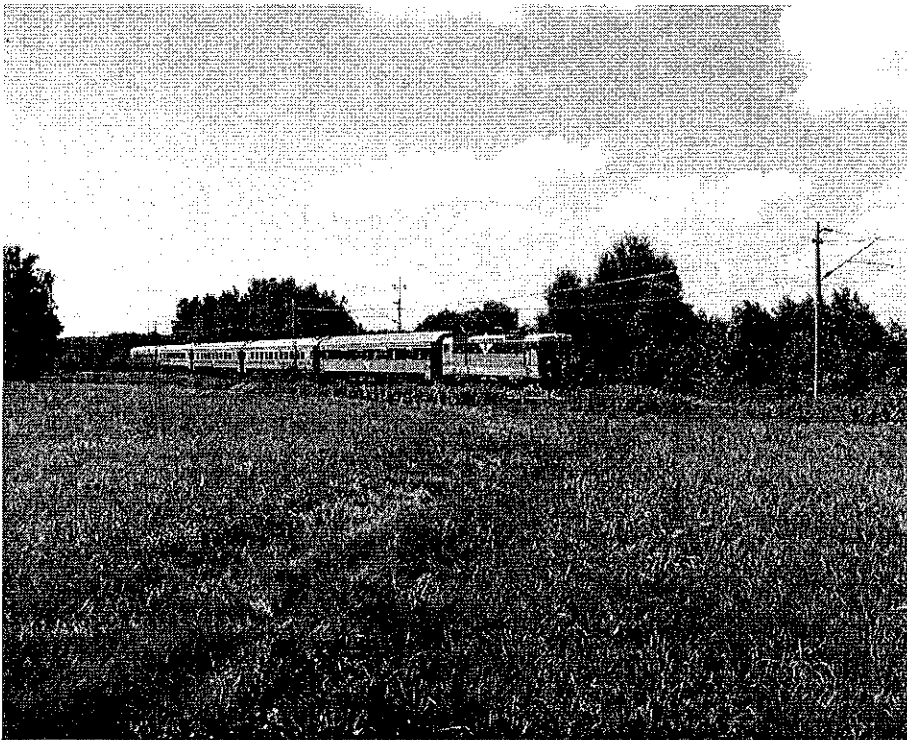
As a first step we obtained the acceleration [dB] against 1/3 oct. within the train's passing time. And the figures below show a train passing by and the results by using MATLAB analysing,



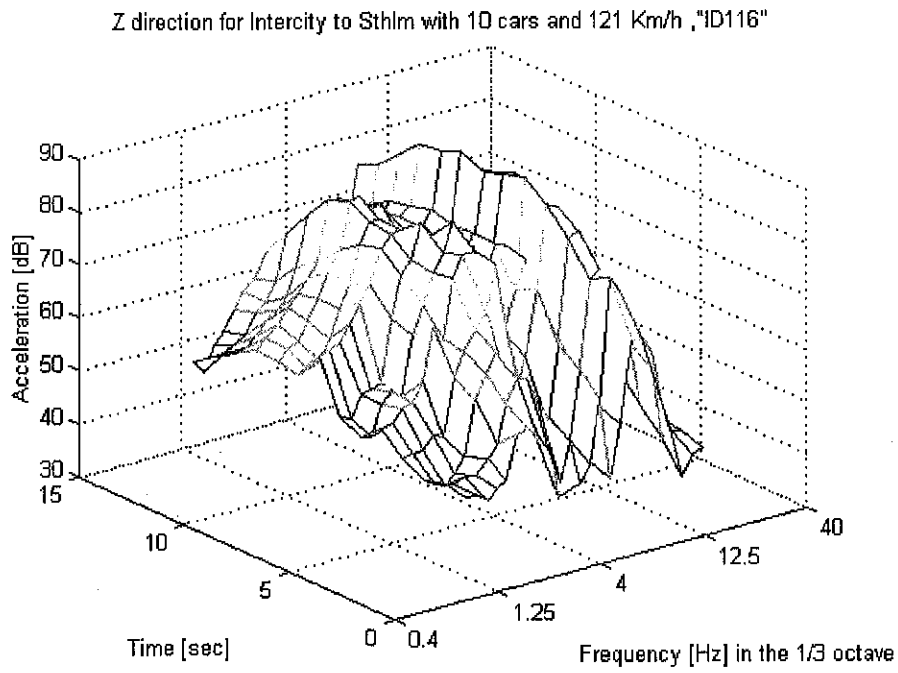
**Figure 7.2** X2000 with 7 cars and 199 Km/h.



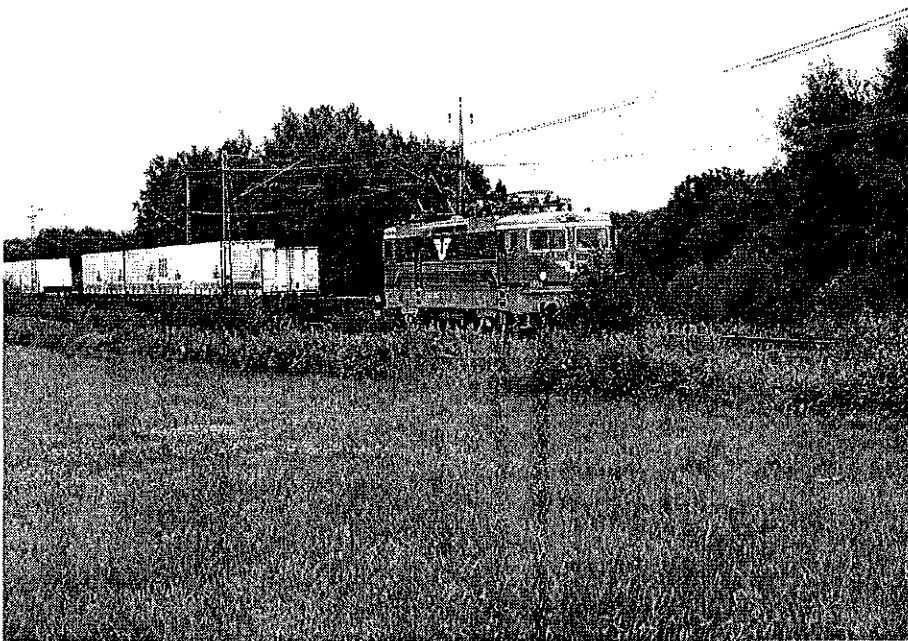
**Figure 7.3** Acceleration levels [dB] against 1/3 Oct. band frequency. The results for the same train in fig7.2



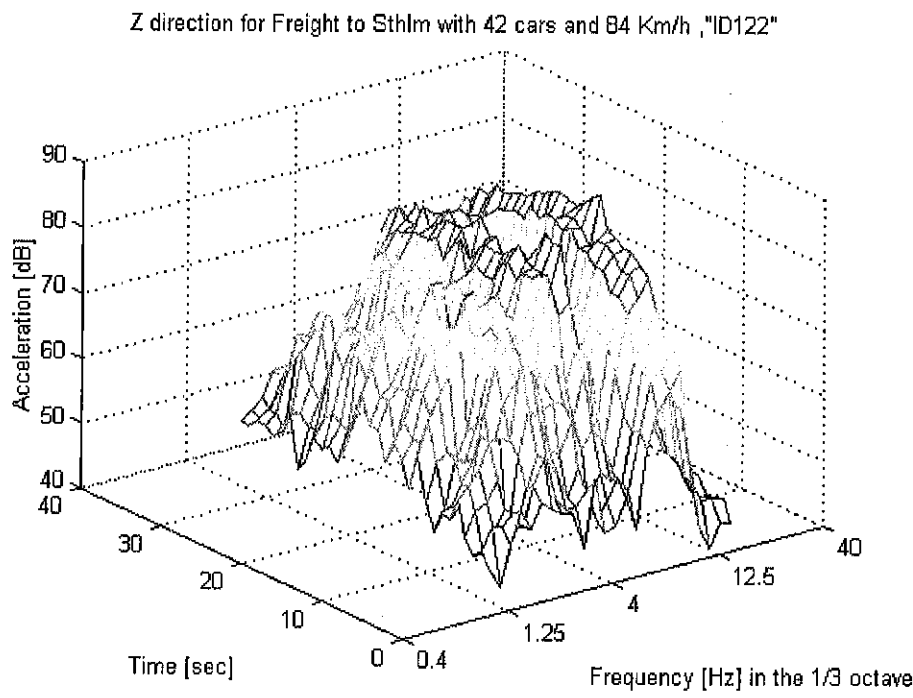
**Figure 7.4** Intercity train with 10 cars and 121 Km/h.



**Figure 7.5** Acceleration levels [dB] against 1/3 oct. band frequency. The results for the same train in Fig 7.4



**Figure 7.6** Freight train with 42 cars and 84 Km/h.

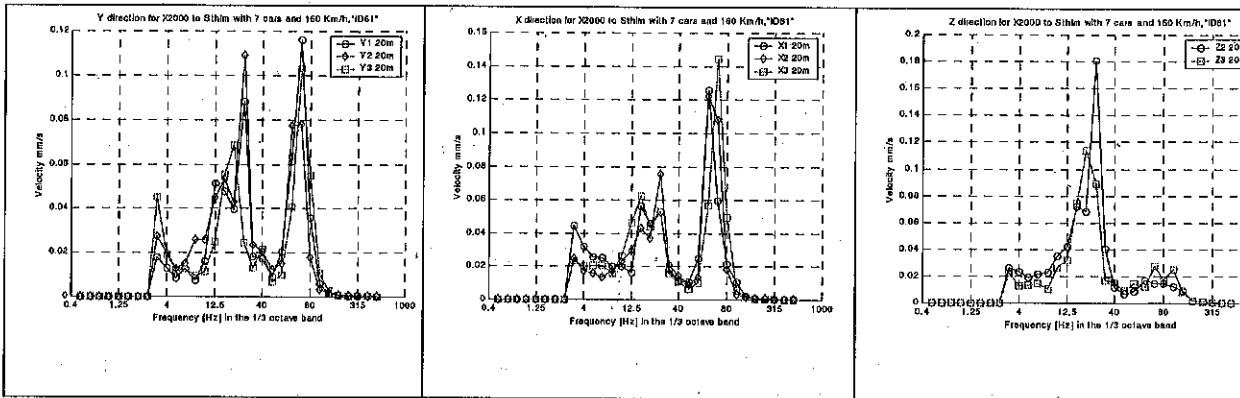


**Figure 7.7** Acceleration levels [dB] against 1/3 Oct. band frequency. The results for the same train in Fig.7.6

**7.3 Measurement Repeatability**

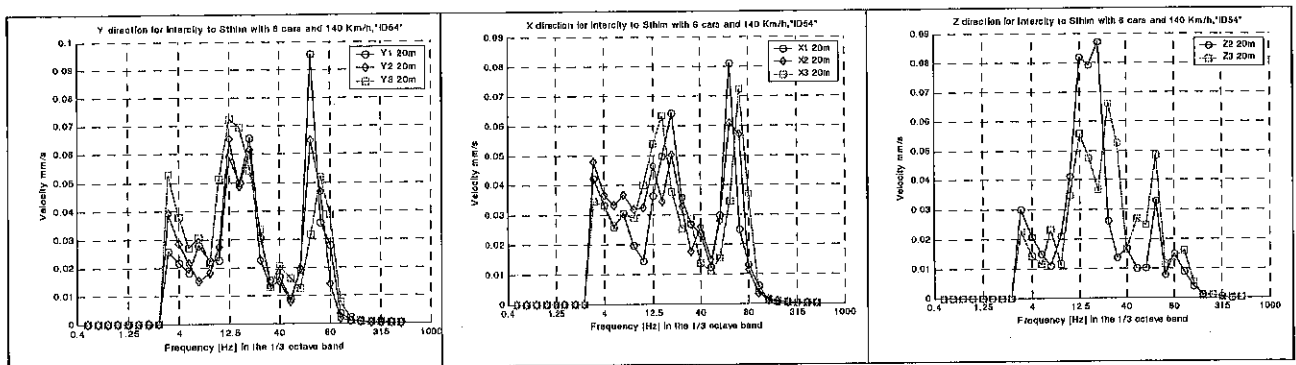
In these measurements all the accelerometers are mounted at 20m away from the centre of the railway track and 20m distance between each other, the accelerometers were 0,5m underground. The results are illustrated below for three different types of trains at the same site: -

Measurements results for an X2000 train:



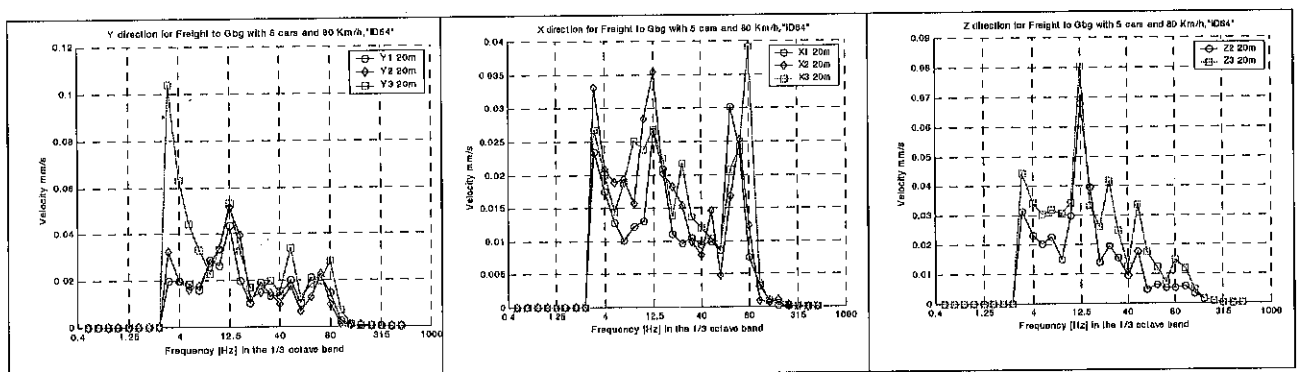
**Figure 7.8** Measurement results for X2000 for the Y, X and Z direction respectively, at the same site at the same distance (20m) at 3 positions 20m apart.

The results for an intercity train:



**Figure 7.9** Measurement results for IC-train for the Y, X and Z direction respectively, at the same site at the same distance (20m) at 3 positions 20m apart.

Results for a freight train:



**Figure 7.10** Measurement results for a freight train for the Y, X and Z direction respectively, at the same site at the same distance (20m) at 3 positions 20m apart.

There are some small differences between the curves for each train individually, e.g. X2000 or the other two trains (intercity and freight train). These differences could be due to many reasons; the most important one is the ground quality for each accelerometer location and the reflection layer underneath the accelerometers. When the wave travel in an identical ground would not suffer any distortion unless the ground type will change, and this leads to higher or lower impedance in the ground, due to that the wave would suffer deflection of reflection in the ground, or the wave could change in shape as well, for e.g. longitudinal wave changes to shear waves or vice versa, all this will effect the wave speed and the amplitude, (one can imagine exactly the same characteristics for the sound waves). The observer can notice some strange peaks less than 3 Hz, it could be because of the background noise signal, which is maybe from the digital recorder or the cables or something else what we don't know.

## 7.4 Dominating Direction of Vibration

If one compares three different trains for three different directions located at several distances from the railway track, one can notice differences in the velocity levels for each direction and distance. These changes depend on all the parameters for the ground vibration. The figures below illustrate measurements for different trains

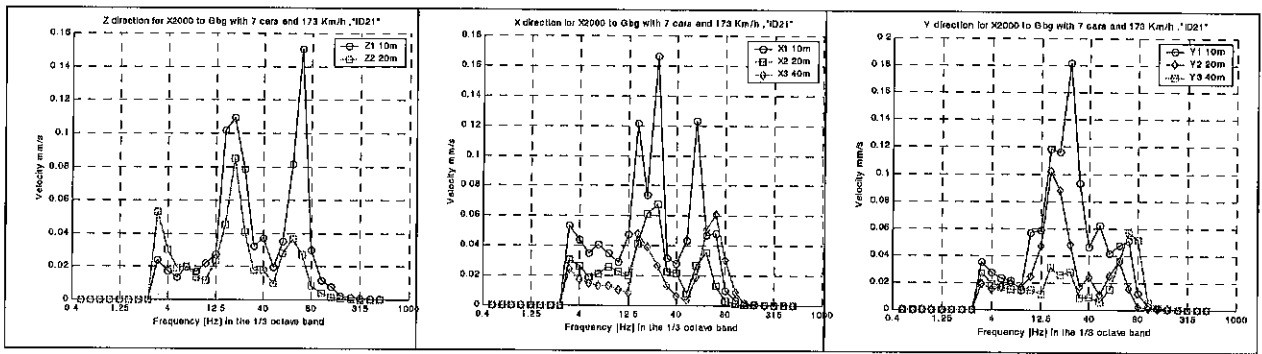


Figure 7.11 Measurements results for X2000 train, to show the dominating direction.

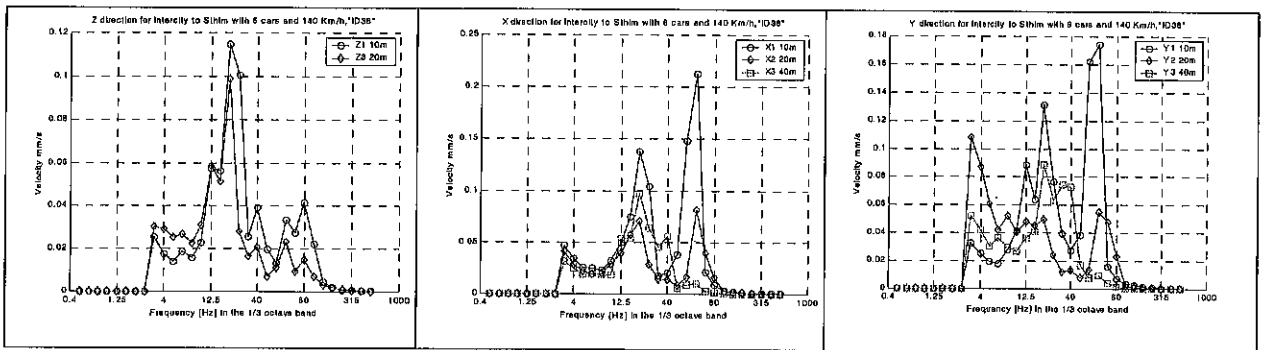


Figure 7.12 Measurements results for intercity train, to show the dominating direction.

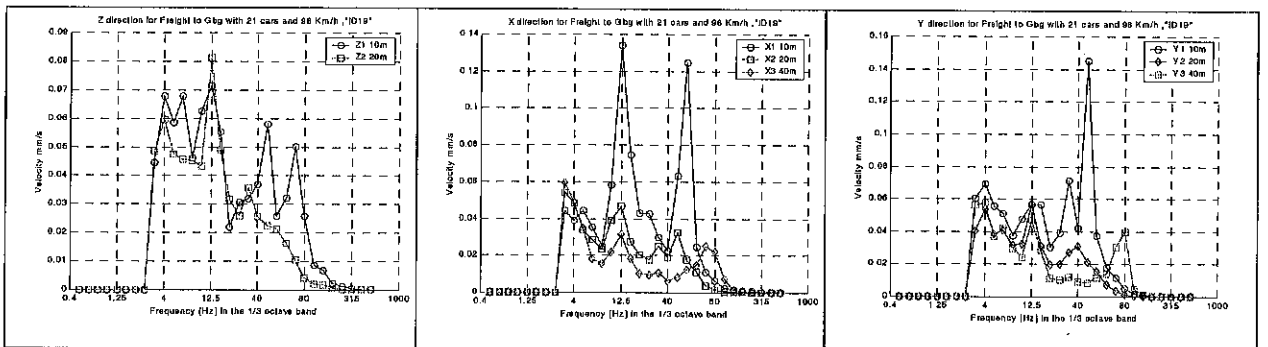


Figure 7.13 Measurements results for freight train, to show the dominating direction.

First, accelerometers located 10m away from the centre of the railway track, are more or less having the same velocity value between 0,15mm/s and 0,18mm/s for all directions. One could say that the accelerometers are close to the vibration source, which generates waves in all the directions at almost the same level. For distant accelerometers a clear decrease in the velocity values appears in *X* and *Y* directions, however *Z* direction does not suffer like the other two directions. The decrement for the maximum value in *Z* direction is less than quarter at 20m and a bit less at 40m, while the decrements at the peaks for *X* and *Y* directions are almost half with 20m distances and another half for 40m distance. One can conclude that the dominating direction at distances longer than about 20m is the *Z* direction.

## 7.5 Vibration Levels as a Function of Train Type

As a rule of thumb the heavier the train the more vibration will be generated. A heavy freight train with average speed generates significant magnitude of vibration at low frequencies range, which could travel further away in the ground comparing with the high frequencies that suffer a lot of damping in the ground. For more details see chapter 8.2.

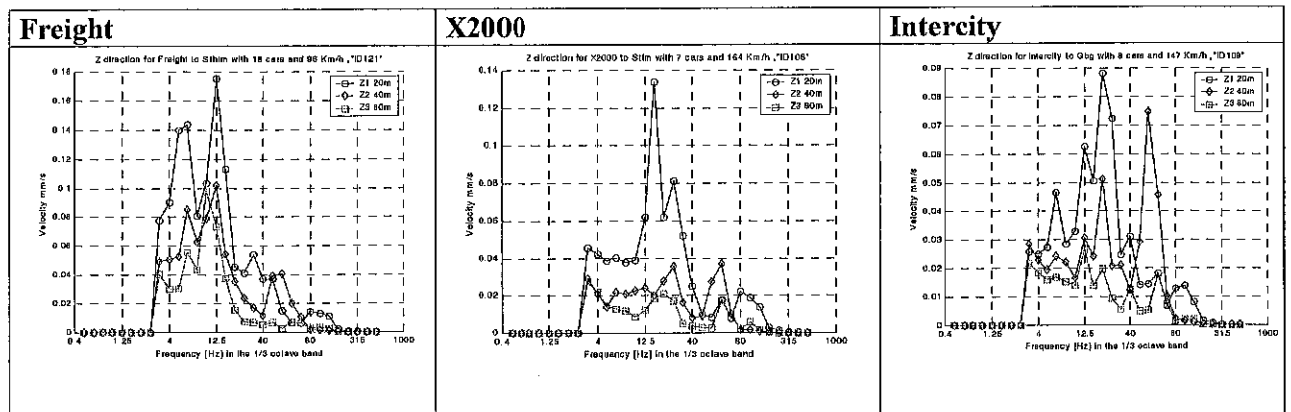


Figure 7.14 Measurements results for three different types of trains.

The figure above shows different trains with different speeds. For this case, the Z direction was chosen to describe the vibration amplitude for the freight train, which is higher than the others in all frequencies bands. One could observe that the velocity amplitude for the low frequencies (at around 12.5 Hz) generated from the freight train doesn't reduce as much as the for the other two train types with the distance.

## 7.6 Dominating frequency

The interesting frequency range is between 0,5 and 100 Hz according to the *ISO 8041* and *SS 460 4861:92*. The frequency has been measured from 0 Hz up to 1000 Hz. But for unknown reason we got very big background signals at the very low frequency range between 0 and 3 Hz. Due to that all the analysed signals were cut below 2,5 Hz.

From the results for more than 120 trains, one can say in general that the dominating frequency was one peak or two around 5 to 12,5 Hz and a second peak which has less amplitude around 80 to 100 Hz. Of course this is not general for all the measured cases, since there are some differences from train to another and for many more factors (see table 5.1), which effect the ground vibrations.

## 8 Prediction and Final Results

### 8.1 General

Depending on the vibration measurements it has been concluded that the ground vibration is affected by many factors. These factors can be summarized as:

- 1) Ground quality (which is the most important factor)
- 2) Train type
- 3) Railway track and the embankment design
- 4) Train speed
- 5) Distance from the rail way track to the building (receiver)
- 6) Building type and the foundation design

In this project a simplification was applied, in which the factors were assumed to be frequency independent and directly related to the time weighting for the maximum velocity  $v_{r.m.s}$  values. According to the literature for previous studies and the results and our experience, the vertical (Z direction) is the most dominating direction compared with the other directions (X and Y).

### 8.2 The General Prediction Formula

According to [43], the following equation describes prediction of ground vibration from railways,

$$V = V_T * F_D * F_S * F_R * F_B \quad (8.1)$$

where

- $V$  = the vibration velocity [mm/s].
- $V_T$  = train vibration level for the particular train type perpendicular to the ground (Z direction) at a reference distance  $D_o$ , from the centre of the railway track and the reference speed  $S_o$  [m/s].
- $F_S$  is a function of the train speed. It could be found by using the equation below

$$F_S = \left( \frac{S}{S_o} \right)^A \quad (8.2)$$

where  $S$  is the train speed and  $S_o$  is the reference speed at which  $V_T$  has been measured.  $A$  can be between 0,5 – 1,5, we will later use  $A = 0,9$ .

- $F_D$  is a function of the distance, which could be obtained by

$$F_D = \left( \frac{D}{D_o} \right)^B \quad (8.3)$$

where  $D$  is the distance to the track and  $D_0$  is the reference distance for which  $V_T$  has been measured.  $B$  will be calculated from the measurements results.

- $F_R$  is a function of the bedrock.  $F_R$  for the bedrock can be 0,7 – 1,3 depending on the type of the railway track if it is single or doubled.
- $F_B$  is a function of the buildings. For Swedish houses the resonance up to 3 floors,  $F_B$  is 2 – 3.

*Parameter A.* When the train is moving on a “perfect” track and rail then there is a steady-state condition. A passenger in the train observes a static deflection of the rail. This deflection has a characteristic wavelength. If this deflection and the characteristic wavelength are independent of the speed of the train then the exponential  $A$  is equal to unity. But there are evidences that the deflection of the rail depends on the speed of the train. The deflection increases with speed and the characteristic wavelength decrease with speed. In that case the exponential  $A$  is greater than unity, say 1,3 – 1,5<sup>1</sup>.

To calculate the exponential  $A$ , we need the same type of train in different speeds; unfortunately we were unable to find cases with large enough differences in speed.

*Exponential B.* As vibrations of the ground mostly consist of Rayleigh waves the exponential  $B$  should be 0,5 to fit the equation for  $F_D$ <sup>2</sup>. But there is also internal damping, dissipation, in the material. So the parameter will be calculated from the obtained data.

As was mentioned before, these measurements were carried out for more than 160 trains from different types, speeds and directions, the problem for these measurements is, one acquire a lot of data from each individual train. To summarize all these data, the trains will be categorized according to the type. The analyses will be for three types of trains, X2000 (fast train), intercity, and freight trains (Heavy train).

The important factors for the prediction formula are, exponential  $A$ , and exponential  $B$ . If we can determine these exponential factors from the measurement results for all the trains types then we can use the formula (8.1) for prediction thus the measurements will be analysed according to find  $A$  and  $B$ , and the procedure of these calculation will be used for all types of trains respectively.

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<sup>1</sup> Bodare

<sup>2</sup> After a short discussion with Bodare, Professor at KTH.

### 8.3 The Measured Vibration Levels $V$

#### 8.3.1 Vibration Levels, $V$ , for X2000 Trains

The value  $V$ , (the vibration level from X2000 train in [mm/s]) was measured for all the trains, and at different distances 10m, 20m, 40m, and 80m respectively. These results are obtained from the MATLAB programme (as mentioned before) for the Z – direction only and for the maximum value. The results are shown below:

**Table 8.1** The values of  $V$  for X2000 at different distances from the track.

<i>V measured for all X2000 trains [mm/s]</i>			
<i>V at 10m</i>	<i>V at 20m</i>	<i>V at 40m</i>	<i>V at 80m</i>
V10_ID21 =0.1506	V20_ID21 =0.0852	V40_ID84=0.0483	V80_ID112=0.026
V10_ID24 =0.0980	V20_ID24 =0.0685	V40_ID93=0.0669	V80_ID114=0.022
V10_ID31 =0.0608	V20_ID31 =0.0367	V40_ID96=0.0692	V80_ID118=0.028
V10_ID33 =0.0864	V20_ID33=0.0813	V40_ID97=0.0379	V80_ID120=0.022
V10_ID41 =0.0940	V20_ID41=0.0575	V40_ID101=0.0414	V80_ID124=0.027
V10_ID43 =0.0940	V20_ID84=0.1113	V40_ID103=0.0451	
V10_ID47 =0.0964	V20_ID93=0.1451	V40_ID108=0.0368	
V10_ID48 =0.1305	V20_ID96=0.1674	V40_ID112=0.0571	
	V20_ID97=0.1270	V40_ID114=0.0416	
	V20_ID101=0.1430	V40_ID118=0.0638	
	V20_ID103=0.1220	V40_ID120=0.0416	
	V20_ID108=0.1339	V40_ID124=0.0593	
	V20_ID112=0.1041		
	V20_ID114=0.0964		
	V20_ID118=0.1326		
	V20_ID120=0.0813		
	V20_ID124=0.1142		
$\bar{V}_{10m} = 0.1013$	$\bar{V}_{20m} = 0.1063$	$\bar{V}_{40m} = 0.0566$	$\bar{V}_{80m} = 0.0255$
$\sigma_{V_{10m}} = 0.0275$	$\sigma_{V_{20m}} = 0.0418$	$\sigma_{V_{40m}} = 0.0162$	$\sigma_{V_{80m}} = 0.0028$

$$\bar{V}_{X2000} = \frac{V_{ID1} + V_{ID2} + \dots + V_{IDn}}{n} \quad (8.4)$$

$$\sigma_{V_{X2000}} = \sqrt{\frac{(V_{ID1} - \bar{V})^2 + (V_{ID2} - \bar{V})^2 + \dots + (V_{IDn} - \bar{V}_n)^2}{n-1}} \quad (8.5)$$

If we compare the average value for the ground – borne vibration it is almost the same at the distances 10m and 20m respectively but they have been damped pretty much at 40m and 80m. Almost 50% from the original signal has been damped at 40m and another 50% at 80m. The explanation is most likely near-field effects at 10m. Thus 10m is not a good reference distance to use when describing ground-borne vibrations.

If we compare the vibration velocity [mm/s] for the highlighted trains, the fastest train with ID 96 and the slowest train with the ID 31, see Annex 1, one can notice that fastest train has the maximum value at 20m while the slowest train has the minimum value at the same distance. And the difference between both speeds is 46 Km/h, which gives quite high difference in the vibration velocity level equal to 0.1307 [mm/s].

### 8.3.2 Vibration Levels, $V$ , for Intercity Trains

The measured vibration velocities for the intercity trains are shown in the table below:

**Table 8.3** The values of  $V$  for the intercity trains at different distances from the track.

<i>V measured for Intercity Trains [mm/s]</i>			
<i>V at 10m</i>	<i>V at 20m</i>	<i>V at 40m</i>	<i>V at 80m</i>
V10_ID17 =0.1391	V20_ID17 =0.0979	V40_ID44 =0.0672	V80_ID98 =0.0229
V10_ID38 =0.1147	V20_ID18 =0.1228	V40_ID45 =0.0638	V80_ID109 =0.0267
V10_ID39 =0.1417	V20_ID32 =0.1251	V40_ID49 =0.0768	V80_ID116 =0.0282
V10_ID44 =0.1132	V20_ID37 =0.0859	V40_ID51 =0.0563	V80_ID119 =0.0227
V10_ID45 =0.1454	V20_ID38 =0.0989	V40_ID83 =0.0660	
V10_ID49 =0.1326	V20_ID39 =0.0785	V40_ID98 =0.0687	
	V20_ID83 =0.0875	V40_ID100 =0.0594	
	V20_ID91 =0.0906	V40_ID109 =0.0746	
	V20_ID98 =0.0982	V40_ID111 =0.0705	
	V20_ID100 =0.0783	V40_ID119 =0.0510	
	V20_ID109 =0.0882		
	V20_ID111 =0.1456		
	V20_ID116 =0.0856		
	V20_ID119 =0.0924		
$\bar{V}_{10m}^* = 0.1311$	$\bar{V}_{20m} = 0.09825$	$\bar{V}_{40m} = 0.06543$	$\bar{V}_{80m} = 0.02512$
$\sigma_V_{10m}^{**} = 0.0139$	$\sigma_V_{20m} = 0.0195$	$\sigma_V_{40m} = 0.0085$	$\sigma_V_{80m} = 0.0027$

\*The mean value has been calculated as before.

\*\*Sigma is calculated as before.

Comparing the two highlights trains, which are the slowest and the fastest, trains obtained during the field measurements, see Annex 1. The train with the ID 119 (156km/h) has more vibrations than the one with the ID 116 (121km/h), at 20m, close to the centre of the railway track. While at 80m (far a way from the track) the slowest trains has more vibrations than the faster one, that could be because of the train with ID 116 has more cars, 10 cars, (which is the longest measured train at 80m from the railway track), than the train with ID119 which has 6 cars, see Annex 1, and that gives the impression of the theory which could be, longer trains with slow speed generates more vibrations at low frequencies than shorter trains with high speeds that produce high vibrations level at high frequencies. As we know from the previous subjects in this study, that the low frequencies do not suffers a significant damping at the far distances as the high frequencies.

**NOTE:** If we look carefully at table 8.3, we can notice that the train with the ID32 has the highest vibration velocity level, but this train was measured in another day and under different measuring conditions (e.g. different weather, different measurements location, etc).

### 8.3.3 Vibration Levels, $V$ , for Freight Trains

The measured vibrations velocities for the freight trains are shown in table 8.5.

**Table 8.5** The values of  $V$  for the intercity trains at different distances from the track.

<i>V measured for Freight Trains [mm/s]</i>			
<i>V 10m</i>	<i>V 20m</i>	<i>V 40m</i>	<i>V 80m</i>
V10_ID19 =0.0716	V20_ID19 =0.0812	V40_ID85 =0.0702	V80_ID95 =0.0315
V10_ID23 =0.0963	V20_ID23 =0.1325	V40_ID95 =0.0560	V80_ID99 =0.0364
V10_ID35 =0.1421	V20_ID35 =0.0376	V40_ID110 =0.0717	V80_ID110 =0.0479
V10_ID46 =0.1172	V20_ID95 =0.0917	V40_ID113 =0.0692	V80_ID113 =0.0691
	V20_ID99 =0.1056	V40_ID122 =0.0693	V80_ID122 =0.0582
	V20_ID110 =0.1114		
	V20_ID113 =0.1109		
	V20_ID122 =0.0952		
$\bar{V}_{10m} = 0.1068$	$\bar{V}_{20m} = 0.1058$	$\bar{V}_{40m} = 0.06728$	$\bar{V}_{80m} = 0.0486$
$\sigma_V_{10m} = 0.03$	$\sigma_V_{20m} = 0.0335$	$\sigma_V_{40m} = 0.006$	$\sigma_V_{80m} = 0.0154$

\*The mean value has been calculated as before.

\*\* Sigma is calculated as before.

If we analyse the freight trains by taking two trains (the highlighted ones), these trains were measured in the same day and under exactly the same measurement conditions. One can notice that, the train with the ID 95 was driven with 99 km/h and it has 7 cars, while the second one with the ID 122 was driven with 84 km/h and it has 42 cars, see Annex 1. At the close distance 20m from the railway track, the faster train has more vibration velocities than the slow one and the difference between the two levels is 0,0035 [mm/s], which is a small difference. But at 80m the slower and longer train, ID 122, has almost double the vibration velocity than the faster and shorter train, ID 95.

The values obtained vary between each other; this variation could be due to the differences in car number or weight of the loads as well. That could be explained by the fact that the attenuation for a long train is less than that of a short train. One could compare this phenomenon with the wave propagation in air, that if we considered the train as point source (short train, less number of cars) then we will have 6 dB less for doubling the distance. On the other hand if we consider the train as line source (long train with many cars), then we will acquire 3 dB less with doubling the distance.

If we compare the average value for the freight trains, which usually have more cars comparing with the other two types (X2000 and intercity), we will find the values are higher for the freight trains than the others at long distances.

## 8.4 Distance Dependence $F_D$

To calculate the Factor  $F_D$  for each train, we should first find the exponential  $B$ .

### 8.4.1 Calculating the Exponential $B$ for X2000

The exponential  $B$  will be calculated for each X2000 individually. All Z direction for all the trains were measured in at least two different distances from the railway track center, 20m is our reference and the other distance were 10m, 40m and 80m.

By applying the equation  $V = V_T * F_D * F_S * F_R * F_B$ , the exponential  $B$  will be calculated as follow

$$\frac{V}{V_{20m}} = \frac{V_T * F_D * F_S * F_R * F_B}{V_T * F_{D,20m} * F_S * F_R * F_B} \quad (8.6)$$

where  $V_T$ ,  $F_S$ ,  $F_R$ , and  $F_B$  are constant for the same train.

So

$$\frac{V}{V_{20m}} = \frac{F_D}{F_{D,20m}} \quad (8.7)$$

and

$$F_D = \left( \frac{D}{D_0} \right)^B \quad (8.8)$$

then with  $D_0 = 20m$

$$\frac{V}{V_{20m}} = \left( \frac{D}{20} \right)^B \quad (8.9)$$

$$\log\left( \frac{V}{V_{20m}} \right) = B \log\left( \frac{D}{20} \right) \quad (8.10)$$

$$B = \frac{\log\left( \frac{V}{V_{20}} \right)}{\log\left( \frac{D}{20} \right)} \quad (8.11)$$

From Eq. (8.11) the exponential  $B$  is calculated. This procedure has been applied for some<sup>1</sup> of the measured X2000 trains and  $B$  was determined for each train pass by. The results are shown in the Table below

---

<sup>1</sup> according to the measurements results.

**Table 8.7** The values of the exponential  $B$  for X2000 at different distances from the track.

<b>The exponential <math>B</math> for all X2000 trains</b>		
<b>10m</b>	<b>40m</b>	<b>80m</b>
Bz_ID21 = -0.8221	Bz_ID84 = -1.2036	Bz_ID112 = -0.9811
Bz_ID24 = -0.5164	Bz_ID90 = -0.1797	Bz_ID114 = -1.0594
Bz_ID31 = -0.7263	Bz_ID93 = -0.9171	Bz_ID118 = -1.1210
Bz_ID33 = -0.0888	Bz_ID96 = -1.0794	Bz_ID120 = -0.9131
Bz_ID41 = -0.7094	Bz_ID97 = -1.7448	Bz_ID124 = -1.0197
Bz_ID43 = -0.7579	Bz_ID101 = -1.7869	
Bz_ID47 = -0.5453	Bz_ID103 = -1.4351	
Bz_ID48 = -0.5288	Bz_ID108 = -1.8627	
	Bz_ID112 = -0.2575	
	Bz_ID114 = -1.2120	
	Bz_ID118 = -0.6626	
	Bz_ID120 = -0.9659	
	Bz_ID124 = -0.9459	
$\bar{B}_{10m} = -0.5869$	$\bar{B}_{40m} = -1.096$	$\bar{B}_{80m} = -1.0187$
$\sigma_B_{10m} = 0.2321$	$\sigma_B_{40m} = 0.5345$	$\sigma_B_{80m} = 0.0786$

\*ID is the train identification when we carried out the measurements and recorded digitally. All the measured trains have individual ID's, see Annex 1.

$$\bar{B} = \frac{B_{ID1} + B_{ID2} + \dots + B_{IDn}}{n} \quad (8.12)$$

$$\sigma_B = \sqrt{\frac{(B_{ID1} - \bar{B})^2 + (B_{ID2} - \bar{B})^2 + \dots + (B_{IDn} - \bar{B})^2}{n-1}} \quad (8.13)$$

The observer can notice that all the values for the exponential  $B$  have negative sign, which means decreasing in the exponential function according to the Eq. (8.6). The exponential  $B$  at 10m varied between 0,5 and 0,8 and the average value is about 0,58, which is rather small. From this we can understand that at close distance from the centre of the railway track the wave does not suffer a lot of damping according to the ground. While at 40m, which is the critical distance from the middle of the railway track, the values for the exponential  $B$  are higher, and they have the negative sign as well. That gives the impression that the waves are still decreasing exponentially due to the ground damping but much more than at 10m. At 80m all the values are higher than at 10m, and almost the same with 40m.

In summary and according to these results, one can say that, the closest to the track the highest vibration velocity one can get. The vibration velocity is damped as a function of distance and ground quality, far away from the track, the lowest vibration velocity, and more stiff ground gives less vibration in the far field.

To apply the prediction formula, an average value could be taken for the exponential  $B$ , at the distances 40m and 80m, so it will be equal to  $-1$ , but at 10m another value for the exponential  $B$ , will be taken this value is approximately equal to  $-0.6$ . The average value has been taken due to the differences in the exponential value  $B$ .

### 8.4.2 Calculating the Factor $F_D$ for X2000 Trains

By using the values for the parameter  $B$ , the factor  $F_D$  could be calculated from Eq. (8.6), these calculations were carried out for some of X2000 trains, intercity trains and freight trains. The results are shown below:

**Table 8.10** The values of  $F_D$  for X2000 at different distances from the track.

<b><math>F_D</math> for X2000</b>		
<b>10m</b>	<b>40m</b>	<b>80m</b>
FD_ID21* =1.7680	FD_ID84 =0.1885	FD_ID112 =0.2567
FD_ID24 =1.4304	FD_ID93 =0.5296	FD_ID114 =0.2302
FD_ID31 =1.6544	FD_ID96 =0.4732	FD_ID118 =0.2114
FD_ID33 =1.0635	FD_ID97 =0.2984	FD_ID120 =0.2820
FD_ID41 =1.6352	FD_ID101 =0.2898	FD_ID124 =0.2433
FD_ID43 =0.9342	FD_ID103 =0.3698	
FD_ID47 =0.6852	FD_ID108 =0.2750	
FD_ID48 =0.6931	FD_ID112 =0.8365	
	FD_ID114 =0.4317	
	FD_ID118 =0.6317	
	FD_ID120 =0.5119	
	FD_ID124 =0.5191	
$\overline{F_D}_{10m} = 1.2330$	$\overline{F_D}_{40m} = 0.4463$	$\overline{F_D}_{80m} = 0.2447$
$\sigma_{F_D}_{10m} = 0.4430$	$\sigma_{F_D}_{40m} = 0.1789$	$\sigma_{F_D}_{80m} = 0.0267$

\*ID is the train identification when we carried out the measurements and recorded digitally. All the measured trains have individual ID.

$$\overline{F_D}_{X2000} = \frac{F_{D\_ID1} + F_{D\_ID2} + \dots + F_{D\_IDn}}{n} \quad (8.14)$$

$$\sigma_{F_D}_{X2000} = \sqrt{\frac{(F_{D\_ID1} - \overline{F_D})^2 + (F_{D\_ID2} - \overline{F_D})^2 + \dots + (F_{D\_IDn} - \overline{F_D})^2}{n-1}} \quad (8.15)$$

### 8.4.3 Calculating the Exponential $B$ for the Intercity Trains

The same equations will be used to calculate the exponential  $B$  for the intercity trains and the results are shown in table 8.8.

**Table 8.8** The values of  $B$  for intercity trains at different distances from the track.

<i>The Exponential B for Intercity Trains</i>		
10m	40m	80m
Bz_ID17 = -0.5068	Bz_ID83 = -0.4062	Bz_ID92 = -0.5942
Bz_ID18 = -0.7528	Bz_ID92 = -1.1690	Bz_ID94 = -0.7887
Bz_ID32 = -0.3279	Bz_ID94 = -0.9155	Bz_ID98 = -1.0501
Bz_ID37 = -0.9149	Bz_ID98 = -0.5161	Bz_ID100 = -0.5737
Bz_ID38 = -0.2150	Bz_ID100 = -0.4003	Bz_ID109 = -0.8615
Bz_ID39 = -0.8519	Bz_ID109 = -0.2422	Bz_ID111 = -1.1299
Bz_ID44 = -0.3766	Bz_ID111 = -1.0456	Bz_ID116 = -0.8021
Bz_ID45 = -0.5942	Bz_ID116 = -0.6362	Bz_ID119 = -1.0128
Bz_ID49 = -0.3939	Bz_ID119 = -0.8583	
Bz_ID51 = -0.4310		
$\bar{B}_{10m}^* = -0.5365$	$\bar{B}_{40m} = -0.6877$	$\bar{B}_{80m} = -0.8516$
$\sigma_B_{10m}^{**} = 0.2351$	$\sigma_B_{40m} = 0.3227$	$\sigma_B_{80m} = 0.204$

\*The mean value has been calculated as before.

\*\*Sigma is calculated as before.

If we compare the exponential  $B$  values between X2000 and intercity trains we can note that, there are some differences for the exponential  $B$  between them. The values for the exponential  $B$  for intercity trains are less than for the X2000 trains, that means the ground damping is less for the waves generated by the intercity trains at the close distances, which means that the intercity trains generates low frequencies more than X2000, and due to the weight for these trains and the length of them, (*most of the measured intercity trains had more than 7 cars*). See Annex 1.

To apply the prediction formula, the average value for the exponential  $B$ , at the far distances was taken.  $B$  will be equal to -0,75. Nevertheless the value at the near distance, 10m differs more than the others, so the value of -0,5, will be considered for the equation at close distances.

#### 8.4.4 Calculating the Factor $F_D$ for the Intercity Trains

$F_D$  could be found by using the values of the calculated  $B$  for the Intercity trains.

**Table 8.11** The values of  $F_D$  for intercity trains at different distances from the track.

<i><math>F_D</math> for Intercity Trains</i>		
10m	40m	80m
FD_ID17 = 1.4209	FD_ID83 = 0.7546	FD_ID92 = 0.4388
FD_ID18 = 1.6850	FD_ID92 = 0.4447	FD_ID94 = 0.3351
FD_ID32 = 1.2552	FD_ID94 = 0.5302	FD_ID98 = 0.2332
FD_ID37 = 1.8855	FD_ID98 = 0.6993	FD_ID100 = 0.4515
FD_ID38 = 1.1607	FD_ID100 = 0.7577	FD_ID109 = 0.3029
FD_ID39 = 1.8049	FD_ID109 = 0.8455	FD_ID111 = 0.2088
FD_ID44 = 0.5933	FD_ID111 = 0.4844	FD_ID116 = 0.3289
FD_ID45 = 0.4388	FD_ID116 = 0.6434	FD_ID119 = 0.2456
FD_ID49 = 0.5792	FD_ID119 = 0.5516	
FD_ID51 = 0.5502		
$\bar{F}_D_{10m}^* = 1.1373$	$\bar{F}_D_{40m} = 0.6346$	$\bar{F}_D_{80m} = 0.3181$
$\sigma_{F_D}_{10m}^{**} = 0.5618$	$\sigma_{F_D}_{40m} = 0.1391$	$\sigma_{F_D}_{80m} = 0.0905$

\*The mean value has been calculated as before.

\*\* Sigma is calculated as before.

The factor  $F_D$  changes from one distance to another, the closer to the track, the higher  $F_D$  one can get. Calculating the Exponential  $B$  for the Freight Trains

To calculate the exponential  $B$  for the freight trains, the same equations and procedures have been followed as before and the results are shown below

**Table 8.9** The values of the exponential  $B$  for freight trains at different distances from the track.

<i>The Exponential B for Freight Trains</i>		
<b>10m</b>	<b>40m</b>	<b>80m</b>
Bz_ID19 = -0.1827	Bz_ID85 = -0.5525	Bz_ID95 = -0.7704
Bz_ID23 = -0.4600	Bz_ID95 = -0.7118	Bz_ID99 = -0.7674
Bz_ID35 = -0.3512	Bz_ID99 = -0.4669	Bz_ID110 = -0.6090
Bz_ID46 = -0.2460	Bz_ID110 = -0.6353	Bz_ID113 = -0.3409
	Bz_ID113 = -0.6793	Bz_ID122 = -0.3545
	Bz_ID122 = -0.4584	
$\bar{B}_{10m}^* = -0.3099$	$\bar{B}_{40m} = -0.586$	$\bar{B}_{80m} = -0.5684$
$\sigma_B_{10m}^{**} = 0.820$	$\sigma_B_{40m} = 0.1186$	$\sigma_B_{80m} = 0.1886$

\*The mean value has been calculated as before.

\*\* Sigma is calculated as before.

The values for the exponential  $B$  are higher for the close distance than the X2000 and intercity trains at 10m, that means, the vibrations are more damped at the close distance according to equation (8.3). While its lower for the far distance at 80m, which means less damping at 80m, and that gives the impression, that these vibrations are generated at low frequencies band, due to the heavy weight and low speeds for these trains when its full with goods. One should consider the length of this kind of trains as well, (*most of the measured trains had more than 20 cars*).

If we compare two freight trains, having different number of cars, the highlighted trains, train with ID95, has 7 cars and train with ID122, has 42 cars, see Annex 1. One could observe that, the exponential  $B$  for the longer train has -0.4584, while the short train has  $B$  equal to -0.7118, which is higher than for the long train. According to eq. (8.11), this means that the vibration generated by the short train is more attenuated than that of the long train at 40m. At 80m the value for the exponential  $B$  for the short train is still high and almost the same as at 40m, -0.7704. While for the long train  $B$  is less, giving the impression that the frequencies generated by this train are mostly low frequencies that propagate for long distances and don't suffer a significant attenuation from the ground. This conclusion could be seen with the other freight trains, ID113, which has 42 cars as well and train with the ID110, having 25 cars. Another explanation is that long trains have more of line source behaviour than short trains. See Annex 1.

All these factors will lead to the fact that in general, this type of trains generates the important low frequencies, which they can travel for long distances in the ground. The most effective vibrations felt by people are generally generated by the freight trains!

The exponential  $B$ , that will be used for the prediction formula at far distances will be the average value at 40m and 80m,  $B$  will be approximately equal to -0,6 and at 10m will be equal to -0,3.

### 8.4.5 Calculating the Factor $F_D$ for Freight Trains

For the freight trains the same procedure was followed to calculate  $F_D$ , and the results shows that the factor is more higher than the two other trains (X2000, intercity) due to the high values for the exponential  $B$  for this type of trains.

**Table 8.12** The values of  $F_D$  for intercity trains at different distances from the track.

<b><math>F_D</math> for Freight Trains</b>		
<b>10m</b>	<b>40m</b>	<b>80m</b>
$F_{D\_ID19} = 1.1350$	$F_{D\_ID85} = 0.6818$	$F_{D\_ID95} = 0.3437$
$F_{D\_ID23} = 1.3756$	$F_{D\_ID95} = 0.6106$	$F_{D\_ID99} = 0.3451$
$F_{D\_ID35} = 1.2756$	$F_{D\_ID99} = 0.7235$	$F_{D\_ID110} = 0.4299$
$F_{D\_ID46} = 0.7111$	$F_{D\_ID110} = 0.6438$	$F_{D\_ID113} = 0.6234$
	$F_{D\_ID113} = 0.6245$	$F_{D\_ID122} = 0.6118$
	$F_{D\_ID122} = 0.7278$	
$\overline{F_D}_{10m}^* = 1.2243$	$\overline{F_D}_{40m} = 0.6686$	$\overline{F_D}_{80m} = 0.4471$
$\sigma_{F_D}_{10m}^{**} = 0.2926$	$\sigma_{F_D}_{40m} = 0.05$	$\sigma_{F_D}_{80m} = 0.1346$

\*The mean value has been calculated as before.

\*\*Sigma is calculated as before.

## 8.5 Speed Dependence $F_S$

$F_S$  is a speed factor, which account to for the effect of the train speed,  $S$ . this factor is given by the equation (8.2). The exponential  $A$  will be chosen to be equal to 0,9, for calculating the factor  $F_S$ .

### 8.5.1 Calculating the Factor $F_S$ for X2000 Trains

To calculate  $F_S$ , (function of train speed), from the equation below

$$F_S = \left( \frac{S}{S_0} \right)^A \quad (8.16)$$

We need to use the average value of the exponential  $A$ , which is as mentioned before will be equal to 0,9. The reference speed is chosen equal to,  $S_0 = 70 \text{ km/h}$ .

By applying the eq. (8.16) one can calculate the factor  $F_S$ , an example for that, we will calculate  $F_S$  for the fastest train and the slowest one for X2000, see Annex 1, where the train with ID96 was driven with 201 Km/h, and the train with the ID31 was driven with 155 km/h.

$$F_S_{ID31} = \left( \frac{155}{70} \right)^{0.9} = 2.0451$$

And

$$F_S_{ID96} = \left( \frac{201}{70} \right)^{0.9} = 2.584$$

The results for the factor  $F_s$ , for X2000, is shown in the table below:

**Table 8.16** The values of the  $F_s$  for X2000 at different distances from the track.

<b><math>F_s</math> for X2000</b>	
FS_ID21 =	2.2576
FS_ID24 =	2.2811
FS_ID31 =	2.0481
FS_ID33 =	2.3981
FS_ID36 =	2.1044
FS_ID40 =	2.1635
FS_ID41 =	2.2224
FS_ID43 =	2.1162
FS_ID47 =	2.2576
FS_ID48 =	2.2341
FS_ID84 =	2.2224
FS_ID90 =	2.2811
FS_ID93 =	2.5492
FS_ID96 =	2.3440
FS_ID97 =	2.5724
FS_ID101 =	2.3981
FS_ID103 =	2.4563
FS_ID104 =	2.3864
FS_ID108 =	2.1516
FS_ID112 =	2.4563
FS_ID114 =	2.1162
FS_ID118 =	2.5608
FS_ID120 =	2.4098
FS_ID124 =	2.5608
<b><math>\overline{F_s} = 2.3217</math></b>	
<b><math>\sigma_{F_s} = 0.1659</math></b>	

The mean value for all  $F_s$  calculated by

$$\overline{F_s}_{-X2000} = \frac{F_{s\_ID1} + F_{s\_ID2} + \dots + F_{s\_IDn}}{n} \quad (8.17)$$

and Sigma is by

$$\sigma_{F_s}_{-X2000} = \sqrt{\frac{(F_{s\_ID1} - \overline{F_s})^2 + (F_{s\_ID2} - \overline{F_s})^2 + \dots + (F_{s\_IDn} - \overline{F_s})^2}{n-1}} \quad (8.18)$$

8.5.2 Calculating the Factor  $F_S$  for Intercity Trains

By using the same equations the factor  $F_S$  for the intercity trains and freight trains were calculated. The results are shown below

As an example we will calculate the factor  $F_S$  for the slowest and the fastest freight trains, see Annex 1. Where the train with the ID116 is the slowest, 121 km/h, measured intercity train, while the train with the ID 119 is the fastest, 156 km/h.

$$F_{S\_ID116} = \left(\frac{121}{70}\right)^{0.9} = 1.6365$$

and

$$F_{S\_ID119} = \left(\frac{156}{70}\right)^{0.9} = 2.057$$

Table 8.17 The values of the  $F_S$  for intercity at different distances from the track.

<i><b><math>F_S</math> for Intercity Trains</b></i>	
FS_ID17 =	2.0213
FS_ID18 =	1.7457
FS_ID32 =	1.8240
FS_ID37 =	1.7939
FS_ID38 =	1.8661
FS_ID39 =	2.1635
FS_ID44 =	1.9259
FS_ID45 =	2.0451
FS_ID49 =	1.9856
FS_ID51 =	1.7457
FS_ID54 =	1.8661
FS_ID83 =	1.9856
FS_ID91 =	1.9618
FS_ID92 =	2.0094
FS_ID94 =	1.9856
FS_ID98 =	1.9498
FS_ID100 =	1.9737
FS_ID109 =	1.9498
FS_ID111 =	2.0332
FS_ID116 =	1.6365
FS_ID119 =	2.0570
$F_{S\_10m^*} = 1.9330$	
$\sigma_{F_S\_10m^{**}} = 0.1253$	

\*The mean value has been calculated as before.

\*\* Sigma is calculated as before.

### 8.5.3 Calculating the Factor $F_S$ for Freight Trains

By using the equation (8.16),  $F_S$  for the freight trains are illustrated as below

The fastest freight train has been recorded in the Annex 1 has the speed 101 km/h with the ID46, and the slowest one was driven with 84 km/h and has the ID122.

$$F_{S\_ID122} = \left( \frac{84}{70} \right)^{0.9} = 1.1783$$

and

$$F_{S\_ID46} = \left( \frac{101}{70} \right)^{0.9} = 1.3909$$

**Table 8.18** The values of the  $F_S$  for freight trains at different distances from the track.

<b><math>F_S</math> for Freight Trains</b>	
FS_ID19 =	1.3537
FS_ID23 =	1.3163
FS_ID35 =	1.3163
FS_ID46 =	1.3909
FS_ID50 =	1.3537
FS_ID85 =	1.2161
FS_ID95 =	1.3661
FS_ID99 =	1.2287
FS_ID105 =	1.2413
FS_ID110 =	1.3163
FS_ID113 =	1.1783
FS_ID115 =	1.3537
FS_ID121 =	1.3288
FS_ID122 =	1.1783
$\overline{F_S}_{10m^*} = 1.2956$	
$\sigma_{F_S}_{10m^{**}} = 0.0722$	

\*The mean value has been calculated as before.

\*\* Sigma is calculated as before.

One can observe that the highest value for X2000 train appears for the train with the ID 96, and the lowest one for the train with the ID 31. From Annex 1, which was documented during the field measurement, the train with ID 96 was driven with speed 201 Km/h while the train with ID 31 was driven with 155 Km/h. For the intercity trains, the fastest train was documented, see Annex 1 with the ID 119, and the slower train was with the ID 116; the speeds were 156 Km/h and 121 Km/h respectively. Freight trains are driven with rather slow speeds, between 80 Km/h and 100 Km/h, the slower train with the ID 122 was driven with 84 Km/h and the fastest train having the ID 46, this train was driven with 101 Km/h.

## 8.6 The Factor $F_R$

The track quality factor  $F_R$ , takes into account the effect on the vibration of the quality of the tracks and the embankment. A massive and stiff embankment below the railway tracks will generally gives less vibration than the “standard”, and a thin and flexible embankment or tracks on grade will give more vibration than “standards”. Furthermore, smooth and well-adjusted tracks with heavy rails gives less vibration compared to rough, low quality tracks.

$F_R$  is a function of the bedrock. The factor  $F_R$  for the bedrock can be 0,7 – 1,3 depending on the type of the railway track, if it is single or doubled. See [43]. For our purpose  $F_R$  will be put equal to 0,8. This value was chosen according to the railway track where our measurements took place, it was a double track (with two directions) and the embankment was thick and deep, that means less generation of vibration, so the value should be less than 1, say 0,8.

## 8.7 The Factor $F_B$

The building amplification factor  $F_B$  is used to transform the free field ground vibration to floor vibration at the most unfavourable place, due to ground foundation coupling and building resonances. This factor is generally frequency dependent, the first natural frequency of the floor in question being of greatest importance. This factor is different from house to house depending on the number of the floors for example or if it is wooden house or rock house foundations. According to reference [43], this factor found to be 2 to 3.

## 8.8 Determination of $V_T$

As a last step to apply the prediction formula,  $V_T$  should be determined for the different trains. After we found most of the parameters for the equation

$$V = V_T * F_D * F_S * F_R * F_B$$

now, one could calculate  $V_T$  for each type of train.  $V_T$  will have a certain value at a certain distance depending on the values of the exponential  $B$ .

For the X2000 trains, the average value of the exponential  $B$ , at 40m and 80m was equal to  $-1.0$ . Then the value  $-1.0$  is for  $B \geq 20m$ , because of the method that we used to calculate the exponential  $B$  was to compare with the distance 20m all the time. See chapter 8.3.1.

The value of the exponential  $A$  was assumed to be 0,9 according to the reference [43], so the factor  $F_S$  was calculated for each type of train individually. The values of the factors  $F_R$ , and  $F_B$  were found to be 0,8 and 2 respectively according to the same reference.

By applying the equation above,  $V_T$  was calculated for the measured X2000 trains, and as a result of taking the average value for  $V_T$  to these trains.  $V_T$  was found to be equal to 0.0337 [mm/s], for distances  $\geq 20m$ .

The same procedure was followed by calculating  $V_T$  for the intercity trains and taking the average value for it.  $V_T$  obtained to be equal to 0.0319 [mm/s], for distances  $\geq 20m$ .

For the last type of trains, freight trains, an equivalent method was followed for finding the values of  $V_T$ . By taking the average value for them,  $V_T$  was obtained to be 0.047, for distances  $\geq 20m$ . Which is higher than the first type of trains.

## 9 Application of the Prediction Formula

From the previous chapters the most important parameter have been found and the information which has been measured can be presented in general form by applying the equation below for the obtained results for  $F_R$ ,  $F_B$ ,  $F_D$ ,  $F_s$ .

$$V = V_T * \left( \frac{D}{D_o} \right)^B * \left( \frac{S}{S_o} \right)^A * F_R * F_B \quad (9.1)$$

This equation could be applied to find the vibration velocities for different train types, and at different distances as well.

Where

$V_T$ : Measured vibration levels for the trains at 20m and 70 Km/h.

$V_T$  for X2000 = 0.0337 [mm/s].

$V_T$  for intercity = 0.0319 [mm/s].

$V_T$  for freight trains = 0.047 [mm/s].

$D$ : Any distance from the centre of the railway track.

$D_o$ : Selected to be 20m, to avoid the influence of the near field waves.

$B$ : Calculated as a distance dependent,  $B$  varied also depending on the train type. The exponential  $B$  was calculated relative the reference distance 20m.

$B$ : for X2000 trains = -1.

$B$ : for intercity trains = -0,7.

$B$ : for freight trains = -0.6.

$S$ : Any speed for any kind of trains.

$S_o$ : Was chosen to be 70 Km/h, to be the reference for all train types, from fast trains (X2000) to slow ones (freight trains).

$A$ : Speed dependent exponential, its value has been assumed to be 0,9 according to [43], unfortunately we couldn't calculate due to that we need more measurements for the trains at very wide-ranging speeds, which we couldn't have it during the measurements stage.

$F_R$ : The track quality factor, according to [43] will be equal to 0,8 in our assignment.

$F_B$ : The building amplification factor, the typical value for it is 2 for the Swedish houses, due to [43].

To compare between the measured values and the values obtained by applying the prediction formula for all the trains

For X2000 at three different distances

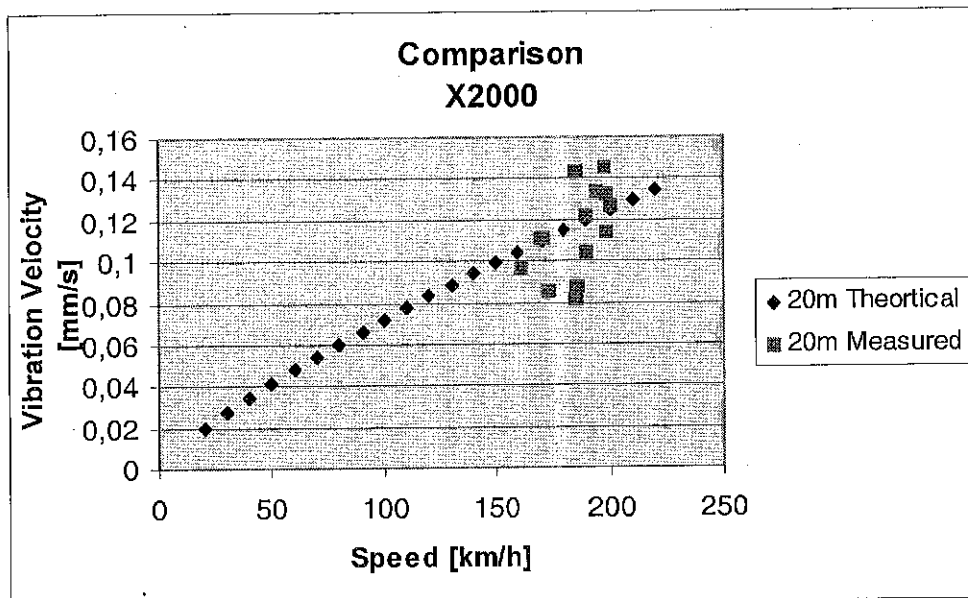


Figure 9.1 Predicted and measured values for X2000.

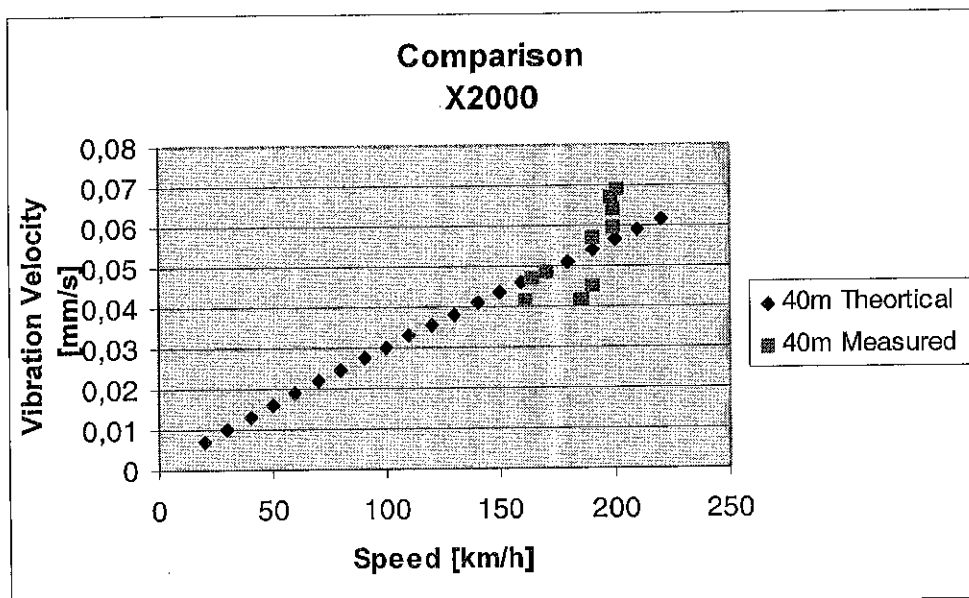
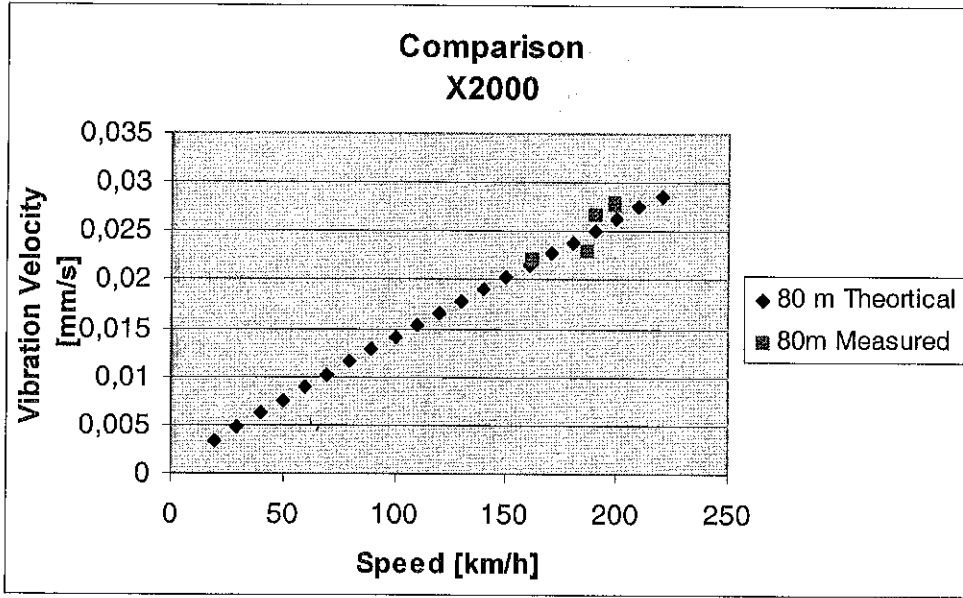


Figure 9.2 Predicted and measured values for X2000.



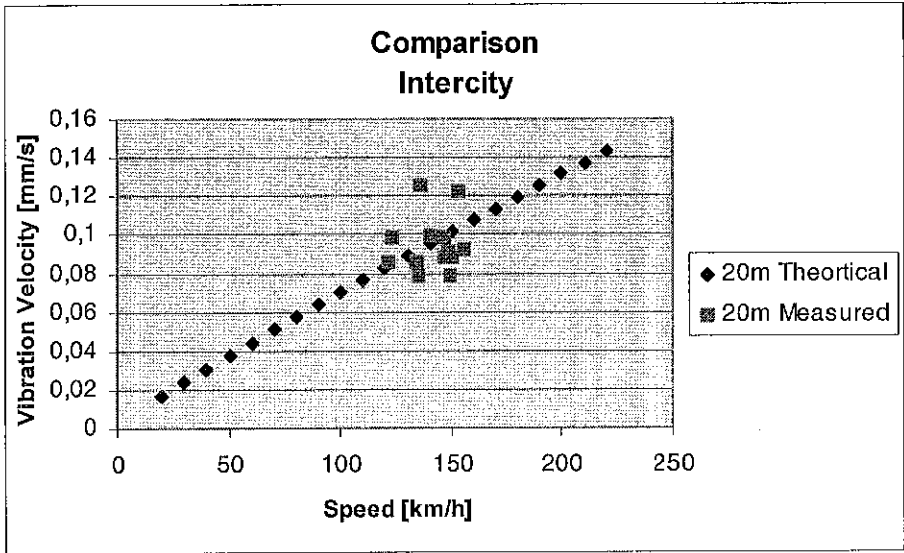


Figure 9.4 Predicted and measured values for IC-trains.

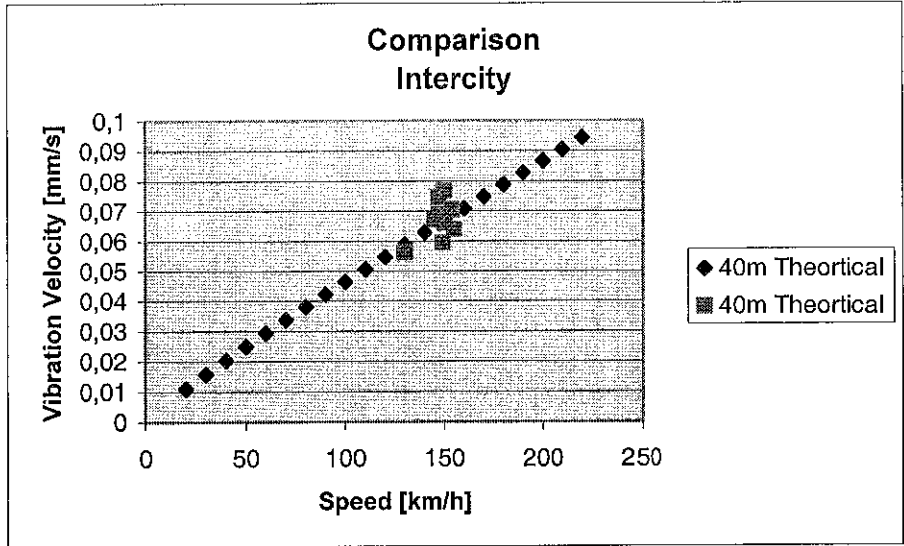


Figure 9.5 Predicted and measured values for IC-trains.

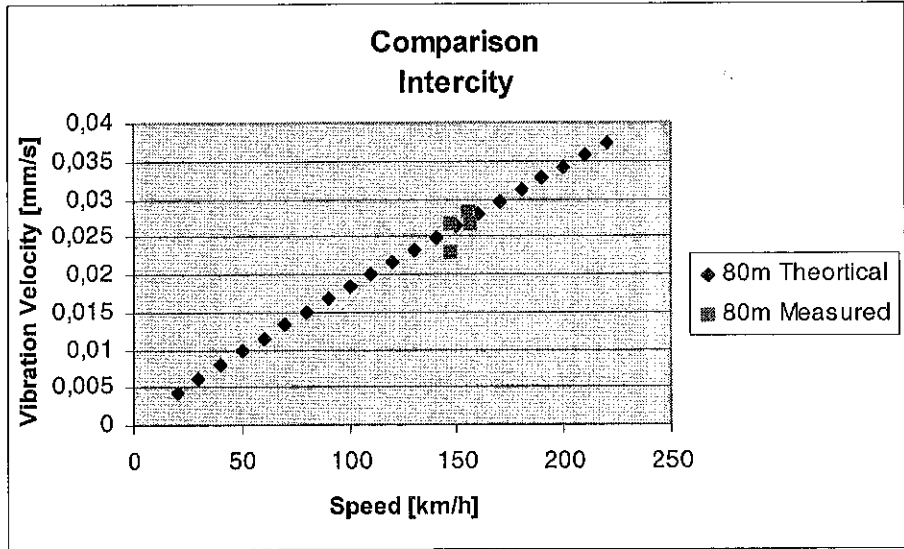


Figure 9.6 Predicted and measured values for IC-trains.

The same equations 9.2, 9.3 and 9.4 were used to confirm the results for the intercity trains

$$\overline{\Delta} = 0.057$$

$$\sigma_{\Delta} = 0.01185$$

And for the freight trains the comparison between the theory and the measurements are shown as below

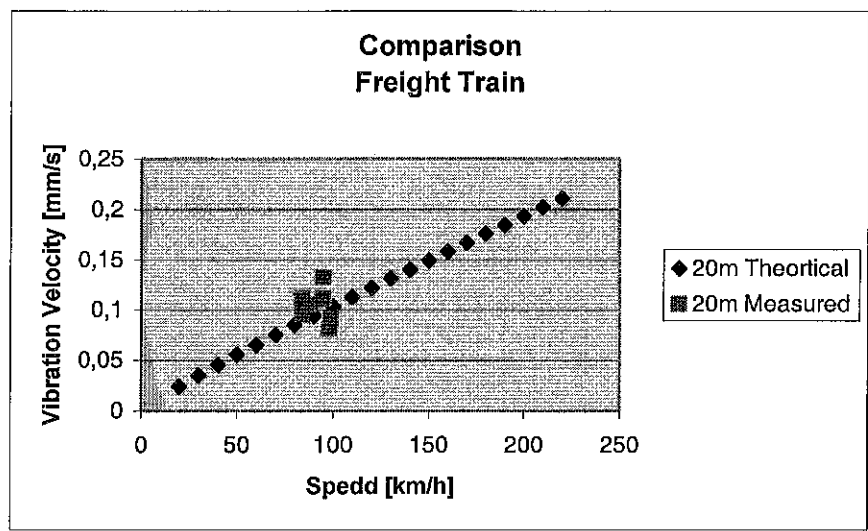


Figure 9.7 Predicted and measured values for freight trains.

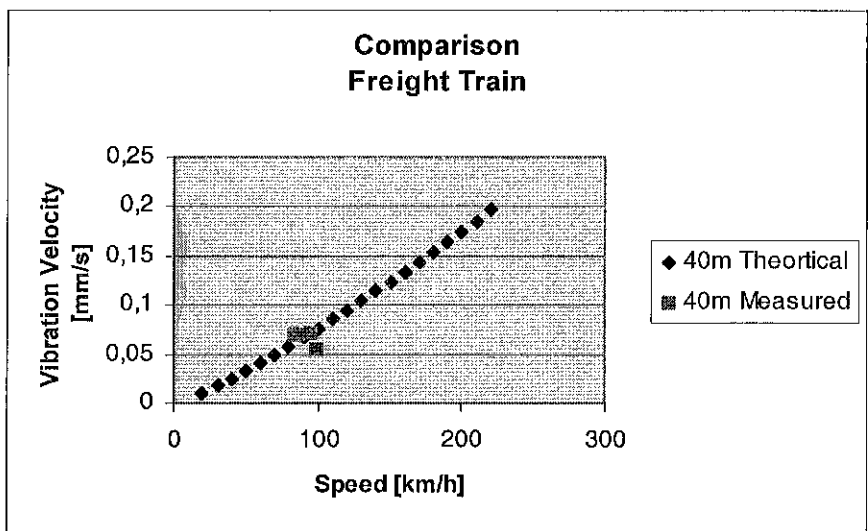
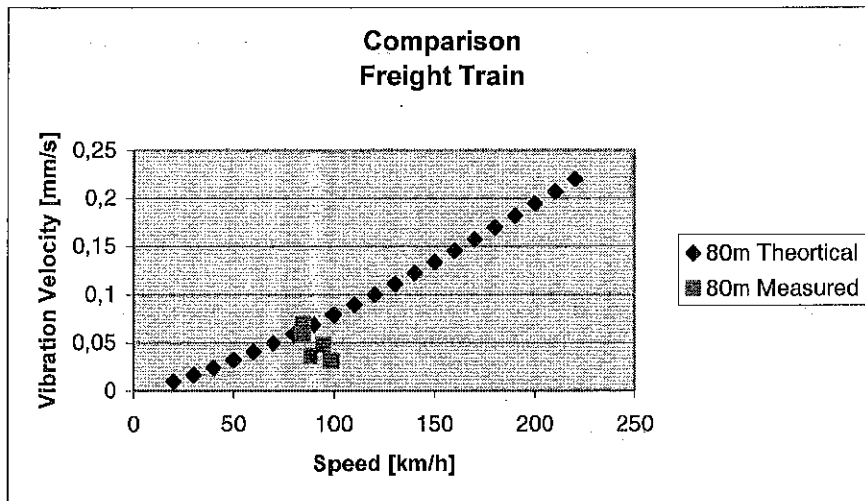


Figure 9.8 Predicted and measured values for freight trains.



**Figure 9.9** Predicted and measured values for freight trains.

The same equations 9.2, 9.3 and 9.4 were used to confirm the results for the freight trains

$$\bar{\Delta} = 0.08254$$

$$\sigma_{\Delta} = 0.036$$

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## ANNEX 1 - Measurement information

Date 11 / 07 /2000

Organisation: Acoustics Department in SP Sveriges Provnings- och Forskningsinstitut

Address Brinell Gatan 4, Box 857, 501 15 Borås

Measurements Location Alingsås, Temp. +15

Instruments Used

Accelerometer 1: Distance from the railway 10

Z direction used,

Charge Sensitivity 10.6 pc/ms<sup>-2</sup>, Type B&K, Serial No. 1161131

X direction used,

Charge Sensitivity 9.87 pc/ms<sup>-2</sup>, Type B&K, Serial No. 775952

Y direction used,

Charge Sensitivity 10.11 pc/ms<sup>-2</sup>, Type B&K, Serial No. 1161130,

Amplifiers

Z direction used,

Type B&K, No. 2635, Output 100 mV/Unit Out, Lower freq. Limit 1 m/s<sup>2</sup>, High freq. Limit 3 kHz.

X direction used,

Type B&K, No. 2635, Output 100 mV/Unit Out, Lower freq. Limit 1 m/s<sup>2</sup>, High freq. Limit 3 kHz.

Y direction used,

Type B&K, No. 2635, Output 100 mV/Unit Out, Lower freq. Limit 1 m/s<sup>2</sup>, High freq. Limit 3 kHz.

Accelerometer 2: Distance from the railway 20

Z direction used, Sensitivity 115.8, Type \_\_\_\_\_, Possessions No. 100913

X direction used, Sensitivity 111.1, Type \_\_\_\_\_, Possessions No. 100617

Y direction used, Sensitivity 114.0, Type \_\_\_\_\_, Possessions No. 100912

Accelerometer 3: Distance from the railway 40

Z direction used, Sensitivity 118.0, Type \_\_\_\_\_, Possessions No. 100911

X direction used, Sensitivity 113.0, Type \_\_\_\_\_, Possessions No. 100914

Y direction used, Sensitivity 117.0, Type \_\_\_\_\_, Possessions No. 100915

ICP System Type Isotron  
2792 B

Model No.

Digital Recorder Type SONY  
208Ax

Model No. PC

Video Camera Type Canon  
1500

Model No. G

Digital Camera Type Olympus  
1400L

Model No. C-

First day measurements, 11/07/2000

On this day, the three directional accelerometers were mounted at 10m, 20m and 40m away from the centre of the railway track. The Z direction of the third accelerometer was omitted.

Measurements No. & I.D	Train type	Car's No.	Speed Km/h	Direction to	Total train length (m)	Time hh:mm
1) ID 16	X2000	7	172	Gbg	151.16	13:32
2) ID 17	Intercity	5	123	Sthlm	111.652	13:45
3) ID 18	Intercity	6	153	Gbg	131.586	14:11
4) ID 19	Freight	21	98	Gbg	523.664	14:20
5) ID 20	Local	2	123	Sthlm		14:41
6) ID 21	X2000	7	173	Gbg	151.16	14:55

Second day measurements, date 12/07/2000

On this day, the three directional accelerometers were mounted at 10m, 20m and 40m away from the centre of the railway track. The Z direction of the third accelerometer was omitted.

Measurements No. & I.D	Train type	Car's No.	Speed Km/h	Direction to	Total train length (m)	Time hh:mm
1) ID 23	Freight	4	95	Gbg	99.736	12:23
2) ID 24	X2000	7	175	Gbg	151.16	13:10
3) ID 25	Intercity	8	127	Sthlm	183.52	13:44
4) ID 27	Freight	5	100	Gbg	124.67	13:45
5) ID 29	Local	2	135	Sthlm		14:42
6) ID 30	X2000	7	144	Gbg	151.16	14:50
7) ID 31	X2000	7	155	Sthlm	151.16	15:14

Third day measurements, Date 13/07/2000

On this day, the three directional accelerometers were mounted at 10m, 20m and 40m away from the centre of the railway track. The Z direction of the third accelerometer was omitted.

Measurements No. & I.D	Train type	Car's No.	Speed Km/h	Direction to	Total train length (m)	Time hh:mm
1) ID 32	Intercity	5	136	Gbg	111.5	10:16
2) ID 33	X2000	7	185	Gbg	151.16	11:02
3) ID 35	Freight	13	95	Sthlm		11:10
4) ID 36	X2000	7	160	Sthlm	151.16	11:20
5) ID 37	Intercity	10	134	Sthlm	231.52	11:47
6) ID 38	Intercity	6	140	Sthlm	131.52	11:50
7) ID39	Intercity	8	135	Gbg	183.52	12:26
8) ID 40	X2000	7	165	Sthlm	151.16	13:09
9) ID 41	X2000	7	170	Gbg	151.16	13:30
10) ID 42	Intercity	5	140	Sthlm	111.52	13:43

#### Fourth day measurements, 14 / 07 /2000

On this day, the three directional accelerometers were mounted at 10m, 20m and 40m away from the centre of the railway track. The Z direction of the 2nd accelerometer was omitted.

Measurements No. & I.D	Train type	Car's No.	Speed Km/h	Direction to	Total train length (m)	Time hh:mm
1) ID 43	X2000	7	151	Gbg	151.16	10:15
2) ID 44	Intercity	7	145	Sthlm	159.086	11:47
3) ID 45	Intercity	9	155	Gbg	207.586	12:10
4) ID 46	Freight	37	101	Gbg	922.558	12:43
5) ID 47	X2000	7	173	Gbg	151.16	13:08
6) ID 48	X2000	7	171	Sthlm	151.16	13:09
7) ID 49	Intercity	7	150	Sthlm	159.086	13:44
8) ID 50	Freight	15	98	Gbg	374	13:59
9) ID 51	Intercity	6	130	Gbg	131.386	14:11
10) ID 52	Local	2	145	Sthlm		14:45

#### Fifth day measurements, date 25/ 07 /2000

In this day, all the accelerometers were mounted at 20m away from the centre of the railway track and 20m distances between each other. These measurements will show the signal coming for the different accelerometers should be more or less the same.

Measurements No. & I.D	Train type	Car's No.	Speed Km/h	Direction to	Total train length (m)	Time hh:mm
1) ID 54	Intercity	6	140	Sthlm	131.52	11:57
2) ID 55	Freight	16	96	Sthlm	398.95	12:05
3) ID 56	Intercity	8	122	Gbg	183.52	12:09
4) ID 57	Intercity	8	126	Gbg	183.52	12:15
5) ID 58	X2000	7	164	Gbg	151.32	12:50
6) ID 61	X2000	7	160	Sthlm	151.16	13:10
7) ID 62	Intercity	5	120	Sthlm	111.52	13:42
8) ID 63	Intercity	6	120	Gbg	131.52	14:11
9) ID 64	Freight	5	80	Gbg	124.67	14:25
10) ID 66	X2000	7	160	Gbg	151.16	15:00
11) ID 67	X2000	7	140	Sthlm	151.16	15:15
12) ID 68	Freight	2	110	Gbg	49.868	15:33
13) ID 69	Intercity	8	110	Sthlm	183.52	15:47
14) ID 71	X2000	7	170	Sthlm	151.16	16:10
15) ID 72	Intercity	8	135	Gbg	183.52	16:13

## Sixth day measurements

On this day, the measurements were carried out at a new location called TORP. The three directional accelerometers were mounted at 20m, 40m and 80m away from the centre of the railway track. The Z direction of the third accelerometer was omitted.

Date 15 /08/000

Measurements No. & I.D	Train type	Car's No.	Speed Km/h	Direction to	Total train length (m)	Time hh:mm
1) ID 75	Freight		112	Gbg		12:43
2) ID 76	X2000		195	Gbg		13:02
3) ID 77	X2000		174	Sthlm		13:11
4) ID 78	Intercity		168	Gbg		13:43
5) ID 83	Intercity	8	150	Gbg		14:13
6) ID 84	X2000	7	170	Sthlm		14:14
7) ID 85	Freight	14	87	Gbg		14:25
8) ID 86	Local	2	155	Sthlm		14:47

## Seventh day measurements, date 16 / 08 /2000

On this day, the measurements were carried out at TORP. The first accelerometers were mounted at 20m away from the centre of the railway track, the second accelerometers were at 40m and the third were at 80m. The X direction for the third accelerometer was omitted. From ID 96 to ID 103, accelerometer No. 3 was moved 2m horizontally from its position. ID 104 to 116 was new measurements for new location of accelerometer No. 2 which, was shifted 2m horizontally. The rest of the measurements carried out after changing at the location for the first accelerometer, which was, moved 2m horizontally and mounted on the surface of the ground.

Measurements No. & I.D	Train type	Car's No.	Speed Km/h	Direction to	Total train length (m)	Time hh:mm
1) ID 90	X2000	7	175	Sthlm		11:11
2) ID 91	Intercity	10	148	Gbg		11:15
3) ID 92	Intercity	6	152	Sthlm		11:44
4) ID 93	X2000	7	198	Gbg	151.16	11:47
5) ID 94	Intercity	8	150	Gbg		12:11
6) ID 95	Freight	7	99	Gbg		12:19
7) ID 96	X2000	7	201	Gbg	151.16	12:52
8) ID 97	X2000	7	200	Sthlm	151.16	13:02
9) ID 98	Intercity	5	147	Sthlm		13:44
10) ID 99	Freight	21	88	Gbg		13:48
11) ID 100	Intercity	6	149	Gbg		14:13
12) ID 101	X2000	7	185	Sthlm	151.16	14:15
13) ID 102	Local	2	161	Sthlm		14:40
14) ID 103	X2000	7	190	Gbg	151.16	14:53
15) ID 104	X2000	7	184	Sthlm	151.16	15:08
16) ID 105	Freight	25	89	Gbg		15:38
17) ID 106	X2000	7	178	Gbg	151.16	15:48
18) ID 107	Intercity	8	125	Sthlm		15:50
19) ID 108	X2000	7	164	Sthlm	151.16	16:10
20) ID 109	Intercity	8	147	Gbg		16:11
21) ID 110	Freight	25	95	Gbg		16:25

22) ID 111	Intercity	6	154	Sthlm		16:45
23) ID 112	X2000	7	190	Gbg	151.16	16:47
24) ID 113	Freight	42	84	Sthlm		17:10
25) ID 114	X2000	7	161	Sthlm	151.16	17:23
26) ID 115	Freight	42	98	Gbg		17:36
27) ID 116	Intercity	10	121	Sthlm		17:37
28) ID 117	Intercity	8	125	Sthlm		17:44
29) ID 118	X2000	7	199	Gbg	151.16	17:55
30) ID 119	Intercity	6	156	Gbg		18:06
31) ID 120	X2000	7	186	Sthlm	151.16	18:08
32) ID 121	Freight	18	96	Sthlm		18:35
33) ID 122	Frieght	42	84	Sthlm		18:38
34) ID 123	Local	2	154	Sthlm		18:45
35) ID 124	X2000	7	199	Gbg	151.16	18:47
36) ID 125	X2000	7	185	Sthlm	151.16	19:10

## ANNEX 2 - Matlab programs

% Programme for analysing the measured signal  
**MATLAB part (1)**

% Read the signal (time history from PCsacn programme)

```
fid=fopen('C:\Program Files\SONY PCscan
MKII\16082000(4)\id124.bin','r');
accelmatrix_tmp=0.001*fread(fid,[8,Inf],'short');
%plot(accelmatrix(:,1:1000))
fs=12000;
```

% DOWNSAMPLING

```
for n=1:8 % Eight channels input
accelmatrix(n,:)=decimate(accelmatrix_tmp(n,:),8);
end
fs=fs/8;
deltat=1/fs;
t=(1:length(accelmatrix(1,:)))*deltat;
```

timestep=2048; %Number of samples within recording the signals

% Analysing for the first channel

```
n=1
for m=1:length(accelmatrix(1,:))/timestep
[a_tmp,f]=pwelch(accelmatrix(n, (m-
1)*timestep+1):m*timestep),timestep*6,fs);
accelsquared_1(m,1:length(a_tmp))=a_tmp';
L1(m,:)=tersband(10*log10(a_tmp'/10^(-12)),f);
end
```

%creating the filter

```
b=exp(-1./fs*(0:4)*timestep);
```

% time weighting (m/s<sup>2</sup>)<sup>2</sup>

```
accelsquared_1_wgt=filter(b,1,accelsquared_1);
```

% acceleration time weighted in dB

```
L1_wgt=10*log10(filter(b,1,10.^(L1/10)));
```

% max acceleration suquered weighted in dB

```
L1_wgt_max_dB=max(L1_wgt);
```

% max acceleration weighted by m/s<sup>2</sup>

```
accel_wgt_max1=sqrt(10.^(L1_wgt_max_dB/10)*10^(-12));
```

% max acceleration weighted by mm/s<sup>2</sup>

```
accel_wgt_max1_mm_ID124=accel_wgt_max1.*1000;
```

```
w=2*pi* [.8 1 1.25 1.6 2 2.5 3.15 4 5 6.3 8 10 12.5 16 20 25 31.5
40 50 63 80 100 125 160 200 250 315 400 500 630 800 1000];
```

% Analysing for the second channel

```
n=2
```

```

for m=1:length(accelmatrix(1,:))/timestep
    [a_tmp,f]=pwelch(accelmatrix(n, (m-
1)*timestep+1):m*timestep), timestep*6, fs);
    accelsquared_2(m,1:length(a_tmp))=a_tmp';
    L2(m,:)=tersband(10*log10(a_tmp'/10^(-12)), f);
end
b=exp(-1./fs*(0:4)*timestep);
accelsquared_2_wgt=filter(b,1,accelsquared_2);
L2_wgt=10*log10(filter(b,1,10.^(L2/10)));
L2_wgt_max_dB=max(L2_wgt);
accel_wgt_max2=sqrt(10.^(L2_wgt_max_dB/10)*10^(-12));
accel_wgt_max2_mm_ID124=accel_wgt_max2.*1000;

% Analysing for the third channel
n=3
for m=1:length(accelmatrix(1,:))/timestep
    [a_tmp,f]=pwelch(accelmatrix(n, (m-
1)*timestep+1):m*timestep), timestep*6, fs);
    accelsquared_3(m,1:length(a_tmp))=a_tmp';
    L3(m,:)=tersband(10*log10(a_tmp'/10^(-12)), f);
end
b=exp(-1./fs*(0:4)*timestep);
accelsquared_3_wgt=filter(b,1,accelsquared_3);
L3_wgt=10*log10(filter(b,1,10.^(L3/10)));
L3_wgt_max_dB=max(L3_wgt);
accel_wgt_max3=sqrt(10.^(L3_wgt_max_dB/10)*10^(-12));
accel_wgt_max3_mm_ID124=accel_wgt_max3.*1000;

% Analysing for the 4th channel
n=4
for m=1:length(accelmatrix(1,:))/timestep
    [a_tmp,f]=pwelch(accelmatrix(n, (m-
1)*timestep+1):m*timestep), timestep*6, fs);
    accelsquared_4(m,1:length(a_tmp))=a_tmp';
    L4(m,:)=tersband(10*log10(a_tmp'/10^(-12)), f);
end
b=exp(-1./fs*(0:4)*timestep);
accelsquared_4_wgt=filter(b,1,accelsquared_4);
L4_wgt=10*log10(filter(b,1,10.^(L4/10)));
L4_wgt_max_dB=max(L4_wgt);
accel_wgt_max4=sqrt(10.^(L4_wgt_max_dB/10)*10^(-12));
accel_wgt_max4_mm_ID124=accel_wgt_max4.*1000;

% Analysing for the 5th channel
n=5
for m=1:length(accelmatrix(1,:))/timestep
    [a_tmp,f]=pwelch(accelmatrix(n, (m-
1)*timestep+1):m*timestep), timestep*6, fs);
    accelsquared_5(m,1:length(a_tmp))=a_tmp';
    L5(m,:)=tersband(10*log10(a_tmp'/10^(-12)), f);
end
b=exp(-1./fs*(0:4)*timestep);
accelsquared_5_wgt=filter(b,1,accelsquared_5);
L5_wgt=10*log10(filter(b,1,10.^(L5/10)));
L5_wgt_max_dB=max(L5_wgt);
accel_wgt_max5=sqrt(10.^(L5_wgt_max_dB/10)*10^(-12));
accel_wgt_max5_mm_ID124=accel_wgt_max5.*1000;

```

```
% Analysing for the 6th channel
```

```
n=6
for m=1:length(accelmatrix(1,:))/timestep
    [a_tmp,f]=pwelch(accelmatrix(n,((m-1)*timestep+1):m*timestep),timestep*6,fs);
    accelsquared_6(m,1:length(a_tmp))=a_tmp';
    L6(m,:)=tersband(10*log10(a_tmp'/10^(-12)),f);
end
b=exp(-1./fs*(0:4)*timestep);
accelsquared_6_wgt=filter(b,1,accelsquared_6);
L6_wgt=10*log10(filter(b,1,10.^(L6/10)));
L6_wgt_max_dB=max(L6_wgt);
accel_wgt_max6=sqrt(10.^(L6_wgt_max_dB/10)*10^(-12));
accel_wgt_max6_mm_ID124=accel_wgt_max6.*1000;
```

```
% Analysing for the 7th channel
```

```
n=7
for m=1:length(accelmatrix(1,:))/timestep
    [a_tmp,f]=pwelch(accelmatrix(n,((m-1)*timestep+1):m*timestep),timestep*6,fs);
    accelsquared_7(m,1:length(a_tmp))=a_tmp';
    L7(m,:)=tersband(10*log10(a_tmp'/10^(-12)),f);
end
b=exp(-1./fs*(0:4)*timestep);
accelsquared_7_wgt=filter(b,1,accelsquared_7);
L7_wgt=10*log10(filter(b,1,10.^(L7/10)));
L7_wgt_max_dB=max(L7_wgt);
accel_wgt_max7=sqrt(10.^(L7_wgt_max_dB/10)*10^(-12));
accel_wgt_max7_mm_ID124=accel_wgt_max7.*1000;
```

```
% Analysing for the 8th channel
```

```
n=8
for m=1:length(accelmatrix(1,:))/timestep
    [a_tmp,f]=pwelch(accelmatrix(n,((m-1)*timestep+1):m*timestep),timestep*6,fs);
    accelsquared_8(m,1:length(a_tmp))=a_tmp';
    L8(m,:)=tersband(10*log10(a_tmp'/10^(-12)),f);
end
b=exp(-1./fs*(0:4)*timestep);
accelsquared_8_wgt=filter(b,1,accelsquared_8);
L8_wgt=10*log10(filter(b,1,10.^(L8/10)));
L8_wgt_max_dB=max(L8_wgt);
accel_wgt_max8=sqrt(10.^(L8_wgt_max_dB/10)*10^(-12));
accel_wgt_max8_mm_ID124=accel_wgt_max8.*1000;
```

```
save('myfile124','accel_wgt_max1_mm_ID124',
'accel_wgt_max2_mm_ID124','accel_wgt_max3_mm_ID124','accel_wgt_max4_mm_ID124',
'accel_wgt_max5_mm_ID124','accel_wgt_max6_mm_ID124','accel_wgt_max7_mm_ID124',
'accel_wgt_max8_mm_ID124')
```

```

figure(1)
mesh (L1_wgt)
grid on
title('Z direction for X2000 to Gbg with 7 cars and 199 Km/h
,"ID124"')
xlabel('Frequency [Hz] in the 1/3 octave band')
zlabel('Acceleration [dB]')
ylabel('Time [sec]')
set(gca,'xticklabel',[0.4 1.25 4 12.5 40 80 315 1000])

```

```

figure(2)
mesh (L2_wgt)
grid on
title('X direction for X2000 to Gbg with 7 cars and 199 Km/h
,"ID124"')
xlabel('Frequency [Hz] in the 1/3 octave band')
zlabel('Acceleration [dB]')
ylabel('Time [sec]')
set(gca,'xticklabel',[0.4 1.25 4 12.5 40 80 315 1000])

```

```

figure(3)
mesh (L3_wgt)
grid on
title('Y direction for X2000 to Gbg with 7 cars and 199 Km/h
,"ID124"')
xlabel('Frequency [Hz] in the 1/3 octave band')
zlabel('Acceleration [dB]')
ylabel('Time [sec]')
set(gca,'xticklabel',[0.4 1.25 4 12.5 40 80 315 1000])

```

```

figure(4)
mesh (L4_wgt)
grid on
title('Z direction for X2000 to Gbg with 7 cars and 199 Km/h
,"ID124"')
xlabel('Frequency [Hz] in the 1/3 octave band')
zlabel('Acceleration [dB]')
ylabel('Time [sec]')
set(gca,'xticklabel',[0.4 1.25 4 12.5 40 80 315 1000])

```

```

figure(5)
mesh (L5_wgt)
grid on
title('X direction for X2000 to Gbg with 7 cars and 199 Km/h
,"ID124"')
xlabel('Frequency [Hz] in the 1/3 octave band')
zlabel('Acceleration [dB]')
ylabel('Time [sec]')
set(gca,'xticklabel',[0.4 1.25 4 12.5 40 80 315 1000])

```

```

figure(6)
mesh (L6_wgt)
grid on

```

```

title('Y direction for X2000 to Gbg with 7 cars and 199 Km/h
','ID124''')
xlabel('Frequency [Hz] in the 1/3 octave band')
zlabel('Acceleration [dB]')
ylabel('Time [sec]')
set(gca,'xticklabel',[0.4 1.25 4 12.5 40 80 315 1000])

```

```

figure(7)
mesh (L7_wgt)
grid on
title('X direction for X2000 to Gbg with 7 cars and 199 Km/h
','ID124''')
xlabel('Frequency [Hz] in the 1/3 octave band')
zlabel('Acceleration [dB]')
ylabel('Time [sec]')
set(gca,'xticklabel',[0.4 1.25 4 12.5 40 80 315 1000])

```

```

figure(8)
mesh (L8_wgt)
grid on
title('Y direction for X2000 to Gbg with 7 cars and 199 Km/h
','ID124''')
xlabel('Frequency [Hz] in the 1/3 octave band')
zlabel('Acceleration [dB]')
ylabel('Time [sec]')
set(gca,'xticklabel',[0.4 1.25 4 12.5 40 80 315 1000])

```

% plotting the Acceleration in [dB]

```

figure (9)
plot (L1_wgt_max_dB)
grid on
title('Z direction for X2000 to Gbg with 7 cars and 199 Km/h
','ID124''')
xlabel('Frequency [Hz] in the 1/3 octave band')
ylabel('Acceleration [dB]')
set(gca,'xticklabel',[0.4 1.25 4 12.5 40 80 315 1000])

```

```

figure (10)
plot (L2_wgt_max_dB)
grid on
title('X direction for X2000 to Gbg with 7 cars and 199 Km/h
','ID124''')
xlabel('Frequency [Hz] in the 1/3 octave band')
ylabel('Acceleration [dB]')
set(gca,'xticklabel',[0.4 1.25 4 12.5 40 80 315 1000])

```

```

figure (11)
plot (L3_wgt_max_dB)
grid on
title('Y direction for X2000 to Gbg with 7 cars and 199 Km/h
','ID124''')
xlabel('Frequency [Hz] in the 1/3 octave band')
ylabel('Acceleration [dB]')
set(gca,'xticklabel',[0.4 1.25 4 12.5 40 80 315 1000])

```

```

figure (12)
plot (L4_wgt_max_dB)
grid on
title('Z direction for X2000 to Gbg with 7 cars and 199 Km/h
,"ID124"')
xlabel('Frequency [Hz] in the 1/3 octave band')
ylabel('Acceleration [dB]')
set(gca,'xticklabel',[0.4 1.25 4 12.5 40 80 315 1000])

figure (13)
plot (L5_wgt_max_dB)
grid on
title('X direction for X2000 to Gbg with 7 cars and 199 Km/h
,"ID124"')
xlabel('Frequency [Hz] in the 1/3 octave band')
ylabel('Acceleration [dB]')
set(gca,'xticklabel',[0.4 1.25 4 12.5 40 80 315 1000])

figure (15)
plot (L6_wgt_max_dB)
grid on
title('Y direction for X2000 to Gbg with 7 cars and 199 Km/h
,"ID124"')
xlabel('Frequency [Hz] in the 1/3 octave band')
ylabel('Acceleration [dB]')
set(gca,'xticklabel',[0.4 1.25 4 12.5 40 80 315 1000])

figure (16)
plot (L7_wgt_max_dB)
grid on
title('X direction for X2000 to Gbg with 7 cars and 199 Km/h
,"ID124"')
xlabel('Frequency [Hz] in the 1/3 octave band')
ylabel('Acceleration [dB]')
set(gca,'xticklabel',[0.4 1.25 4 12.5 40 80 315 1000])

figure (17)
plot (L8_wgt_max_dB)
grid on
title('Y direction for X2000 to Gbg with 7 cars and 199 Km/h
,"ID124"')
xlabel('Frequency [Hz] in the 1/3 octave band')
ylabel('Acceleration [dB]')
set(gca,'xticklabel',[0.4 1.25 4 12.5 40 80 315 1000])

% plotting the Velocity in [mm/s]

figure (18)
hold on

plot (accel_wgt_max1_mm_ID124./w,'b-')
grid on
title('"ID51" Intercity to Gbg with 6 cars and 98 Km/h ')
xlabel('Frequency [Hz] in the 1/3 octave band')
ylabel('Velocity mm/s')
set(gca,'xticklabel',[0.4 1.25 4 12.5 40 80 315 1000])

figure (19)

```

```

plot (accel_wgt_max2_mm_ID124./w,'r:')
grid on
title('X direction for X2000 to Gbg with 7 cars and 199 Km/h
,'ID124"')
xlabel('Frequency [Hz] in the 1/3 octave band')
ylabel('Velocity mm/s')
set(gca,'xticklabel',[0.4 1.25 4 12.5 40 80 315 1000])

```

```

figure (20)
plot (accel_wgt_max3_mm_ID124./w,'g--')
grid on
title('Y direction for X2000 to Gbg with 7 cars and 199 Km/h
,'ID124"')
xlabel('Frequency [Hz] in the 1/3 octave band')
ylabel('Velocity mm/s')
set(gca,'xticklabel',[0.4 1.25 4 12.5 40 80 315 1000])

```

```

figure (21)
plot (accel_wgt_max4_mm_ID124./w,'b:')
grid on
title('X direction for X2000 to Gbg with 7 cars and 199 Km/h
,'ID124"')
xlabel('Frequency [Hz] in the 1/3 octave band')
ylabel('Velocity mm/s')
set(gca,'xticklabel',[0.4 1.25 4 12.5 40 80 315 1000])

```

```

figure (22)
plot (accel_wgt_max5_mm_ID124./w,'m--')
grid on
title('Y direction for X2000 to Gbg with 7 cars and 199 Km/h
,'ID124"')
xlabel('Frequency [Hz] in the 1/3 octave band')
ylabel('Velocity mm/s')
set(gca,'xticklabel',[0.4 1.25 4 12.5 40 80 315 1000])

```

```

figure (23)
plot (accel_wgt_max6_mm_ID124./w,'c--')
grid on
title('Z direction for X2000 to Gbg with 7 cars and 199 Km/h
,'ID124"')
xlabel('Frequency [Hz] in the 1/3 octave band')
ylabel('Velocity mm/s')
set(gca,'xticklabel',[0.4 1.25 4 12.5 40 80 315 1000])

```

```

figure (24)
plot (accel_wgt_max7_mm_ID124./w,'b:')
grid on
title('X direction for X2000 to Gbg with 7 cars and 199 Km/h
,'ID124"')
xlabel('Frequency [Hz] in the 1/3 octave band')
ylabel('Velocity mm/s')
set(gca,'xticklabel',[0.4 1.25 4 12.5 40 80 315 1000])

```

```

figure (25)
plot (accel_wgt_max8_mm_ID124./w,'k--')
grid on
title('Y direction measurements at 40m for Intercity to Gbg with 9
cars and 155 Km/h ')
xlabel('Frequency [Hz] in the 1/3 octave band')
ylabel('Velocity mm/s')
set(gca,'xticklabel',[0.4 1.25 4 12.5 40 80 315 1000])

```

```

hold off

% plotting the directions at different distances

figure (27)
hold on

plot (accel_wgt_max1_mm_ID124./w,'ko-')
plot (accel_wgt_max4_mm_ID124./w,'bd-')
plot (accel_wgt_max7_mm_ID124./w,'rs-')

grid on
title('Z direction for X2000 to Gbg with 7 cars and 199 Km/h
,"ID124"')
xlabel('Frequency [Hz] in the 1/3 octave band')
ylabel('Velocity mm/s')
set(gca,'xticklabel',[0.4 1.25 4 12.5 40 80 315 1000])
legend('Z1 20m','Z2 40m','Z3 80m')
hold off

figure(28)
hold on

plot (accel_wgt_max2_mm_ID124./w,'ko-')
plot (accel_wgt_max5_mm_ID124./w,'bs-')

grid on
title('X direction for X2000 to Gbg with 7 cars and 199 Km/h
,"ID124"')
xlabel('Frequency [Hz] in the 1/3 octave band')
ylabel('Velocity mm/s')
set(gca,'xticklabel',[0.4 1.25 4 12.5 40 80 315 1000])
legend('X1 20m','X2 40m')
hold off

figure(29)
hold on
plot (accel_wgt_max3_mm_ID124./w,'ko-')
plot (accel_wgt_max6_mm_ID124./w,'bd-')
plot (accel_wgt_max8_mm_ID124./w,'rs-')
grid on
title('Y direction for X2000 to Gbg with 7 cars and 199 Km/h
,"ID124"')
xlabel('Frequency [Hz] in the 1/3 octave band')
ylabel('Velocity mm/s')
set(gca,'xticklabel',[0.4 1.25 4 12.5 40 80 315 1000])
legend('Y1 20m','Y2 40m','Y3 80m')
hold off

```

## MATLAB part (2)

```

%Tersband version
%function L=tersband(Lin,fin);

```

```

%Summerar SPL för tersband 100hz - 10khz
%Inparametrar
%Lin - Vektor med SPL för smalband
%fin - Bandfrekvens för smalband
%Utparameter
%L - Vektor med SPL för tersband 50hz - 10khz
%Lokalt
%f - vektor med mittfrekvenser i tersband

function L=tersband(Lin,fin);
for variabel =-26:-3 %1.6hz - 500hz
    % f(variabel+14)=1000*10^(variabel/10);%ekvation enligt IEC
    1260 annex A
    f(variabel+35)=1000*10^(variabel/10);%ekvation enligt IEC 1260
    annex A
end
upp=10^(1/20);
ner=10^(-1/20);
for n=1:length(f);
    I=find( (fin>(f(n)*ner)) & (fin<(f(n)*upp)) );

    %if isempty(I)
    %    error('Frekvebsband tomt')
    %end
    L(n)=10*log10( sum(10.^(Lin(I)./10)) ); % Summation of SPL
end

```

## ANNEX 3 - Characteristics of Different Trains

These information are based on study were carried for all the Swedish trains, See [34].

### Explanation

In SLM (Svenska lok och motorvagnar) SI-units are constantly being used. For whom looking to compare to older units are comparative figures and remarks given below.

**Axle arrangement** is given according to the European standards, where fixed axles in the framework are characterized by numbers for running shafts and with letters for axle shafts. Running shafts and bogie shafts are represented by '.

Example: 1'C1' means an engine with three connected shafts in a framework and two running shafts. Bo'Bo' signifies an engine with two bogies with each two individually driven shafts.

**Type** indicates main type of the vehicle as for example electrical bogie engine or diesel hydraulic concerning motor engines.

**Output power / hourly output** is stated in kW (kilowatt). If the output power in kW is multiplied by 1.36 one gets the effect measured in horsepower. Regarding to the electrical vehicles, the time effect is usually mentioned via the definition for the velocity, which means the effect of the vehicle can be accomplish per hour at this velocity.

**Motor control** indicates if, on an electrical vehicle, the current and by that also the velocity to the engines are being regulated on the transformers primary / high tension-side or the secondary / low tension side.

Low tension regulated engines can be divided into the following types:

Emk = Downside regulated electro magnetically contactors.

Epk = Down side regulated electro-air driven contactors.

Tyr = Down side regulated theorester.

Väx = Downside regulated vibrator (alternator).

High tension regulated engines are only of the type Ma, which has a automatic control system of the type Lko (= upside regulated tap-change gear)

**Running steps** are given in which amount of steps the engine tension (voltage?) can be regulated on a vehicle with electrically traction motors. At thyristor-steering (text says 'and' here - must be wrong) gradual driving-positions are missing. Distinction has not been made according to different types of driving-positions (connected in series / connected in parallel or breaking-positions).

**Sth** gives the greatest allowed velocity in km/h.

**Transmission:** states how the driving power is transmitted from engine to axle shaft. This is showed either by system-description (ex. coupling rod) or type (Voith L33y). The last case indicates the transmission system (ex. Hydraulic) in type.

**Maximal length** gives length of bumpers if this is the vehicles maximum length.

Regarding vehicles with automatically-couple is length over couple the maximum length and is given as "läng ö./k. (längd över stötplan/koppel)".

**Wheelbase** gives the distance between the outer-shafts of a vehicle. On bogie-vehicles the distance is given between the outer-shafts in the bogie plus the centre-distance

between the bogies. If the bogie centre isn't placed at the centre of the bogie a remark is made on the type-page.

**Weight in w.o** gives the vehicles weight in service (eg working mode).

**Adhes. Weight** gives the load on the axel shaft.

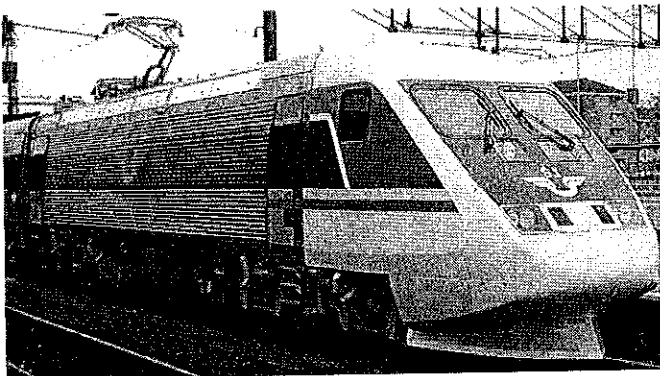
**Dynamic Weight** The weight that's being used at calculation of train-mass/brake-rate where consideration is made to the rotating mass of the vehicle.

**Brake-position G/P/R (swedish: bromsläge)** gives various speediness and braking-power of the brakes. Breaking-position G (s.c. "godstågsbroms" - goods train) has a slower addition and loosening of the brakes than position P (s.c. "persontågsbroms" - passenger train) and R (s.c. "rapidbroms"). Position R gives a higher air-driven-pressure from the pilot valve to the wheel brake cylinder which leads to a stronger breaking-force than position G and P. Breaking-position G with extra air-supply (s.c. "matarledning" - antenna feed system) is named M.

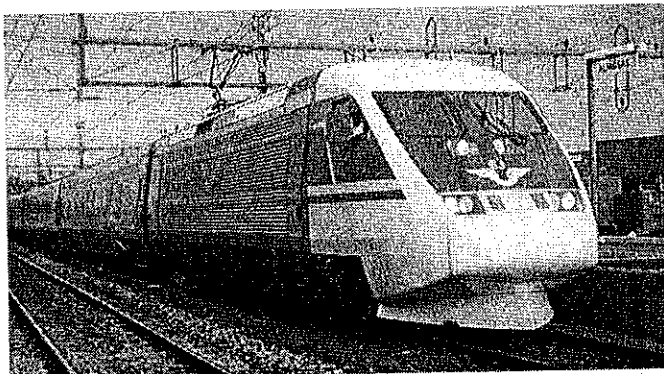
## X2000

The fast train X2000 has different types of construction and conditions depending on the need of use for them.

### SJ X2



X2000 2020 in Uppsala.



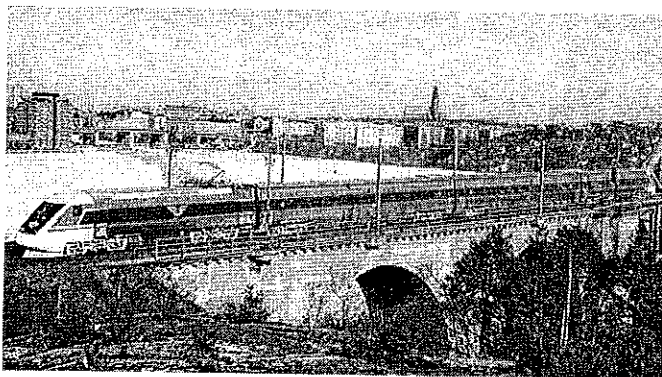
X2000 in Alingsås.

Type	Drive	Train set *	Units
Effect	4*815=3260	3260	KW
Tract. Motor	MJA 385 - 2	MJA 385 - 2	
Motor Control	Low voltage	Low voltage	
Running steps	Step loose	Step loose	
Transmission	Tube hole axel	Tube hole axel	
Maximum length	16980	139310	mm
Wheelbase	2900+9500	133950	mm
Driv. wheel diam.	1100	1100/880	mm
Seating cap. 1 kl	--	230	Person
Weight in w.o.	73	318	Ton
Adhes. Weight	73	73	Ton
Max. Axel load	18.25	18.25	Ton
Start. Trac. Effort	160	160	kN
Brake weight	125	513**	Ton
Dynamic weight	78	78	Ton
Pantograph	WBL88	WBL88	
Max. Speed	200	200	Km/h

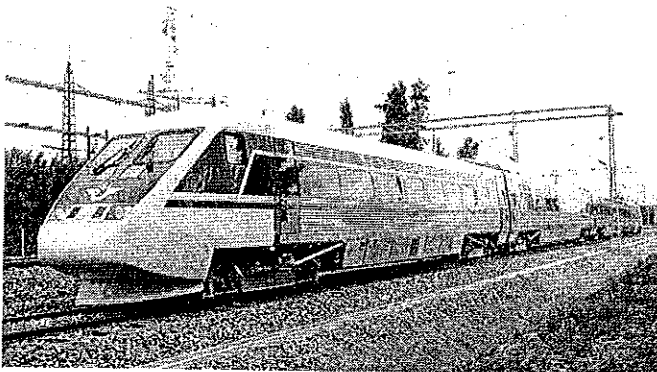
\* Normal train set consist of X2 + UA2 + UA2 + URA2 + UA2 + UA2X.

\*\* With magnet braking + 180 Ton (total 693 Ton).

SJ X2 – 2



X2000 2023 + UB2 2822 + UBS2 2901 + UA2X 2524 in Stockholm.



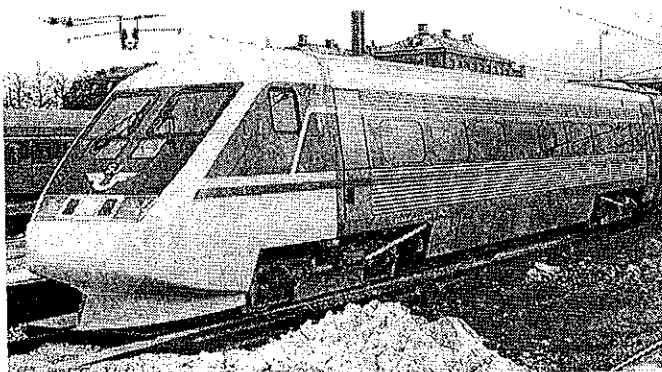
X2000 2023

Type	Drive	Train set *	Units
Effect	4*815=3260	3260	KW
Tract. Motor	MJA 385 - 2	MJA 385 - 2	
Motor Control	Low voltage	Low voltage	
Running steps	Step loose	Step loose	
Transmission	Tube hole axel	Tube hole axel	
Maximal length	16980	139310	mm
Wheelbase	2900+9500	133950	mm
Driv. wheel diam.	1100	1100/880	mm
Seating cap. 1 kl	--	29	Person
Seating cap. 2 kl	--	143	
Weight in w.o.	73	214	Ton
Adhes. Weight	73	73	Ton
Max. Axel load	18.25	18.25	Ton
Start. Trac. Effort	160	160	kN
Brake weight	125	513**	Ton
Dynamic weight	78	78	Ton
Pantograph	WBL88	WBL88	
Max. Speed	200	200	Km/h

\* Normal train set consist of X2 + UB2 + UBS2 + UA2X.

\*\* With magnet braking + 180 Ton (total 693 Ton).

SJ UA2X, UB2X



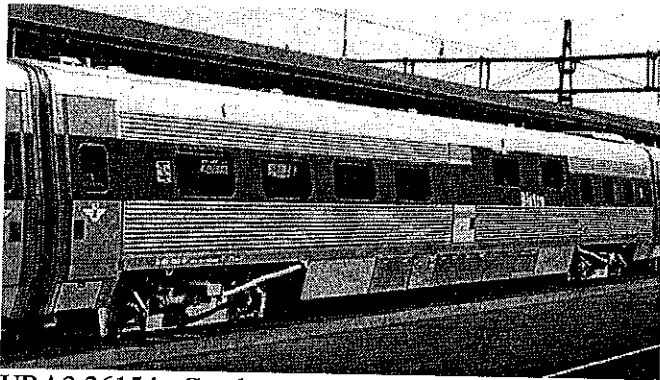
UA2X 2521 in Göteborg.

	UA2X	UB2X	Units
Maximum length	21980	21980	mm
Wheelbase	2900+14500	2900+14500	mm
Driv. wheel diam.	880	880	mm
Seating cap. 1 kl	29+2**	--	Person
Seating cap. 2 kl	--	49+1**	Person
Weight in w.o.	55	55	Ton
Max. Speed	200	200	Km/h
Brake weight	75*	75*	Ton

\* With magnet brake + 36 ton.

\*\* Handicap places.

## SJ URA2, URA2G, URB2, UBS2



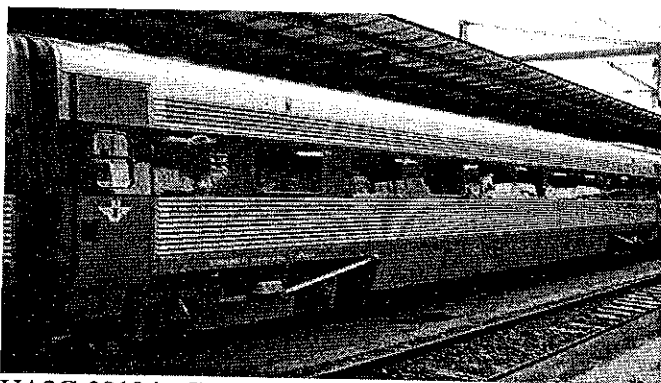
URA2 2615 in Göteborg.

Kind	URA2	URA2G	URB2	UBS2	Units
Maximum length	24400	24400	24400	24400	mm
Wheelbase	2900+17700	2900+17700	2900+17700	2900+17700	mm
Driv. wheel diam.	880	880	880	880	mm
Seating cap. 1 kl	22+4**	22+11	--	--	Person
Seating cap. 2 kl	--	--	29+11**	67	Person
Weight in w.o.	52	52	52	52	Ton
Max. Speed	200	200	200	200	Km/h
Brake weight	75*	75*	75*	75*	Ton

\* With magnet brakes + 36 ton.

\*\* In the bistro.

## SJ UA2, UA2G, UB2



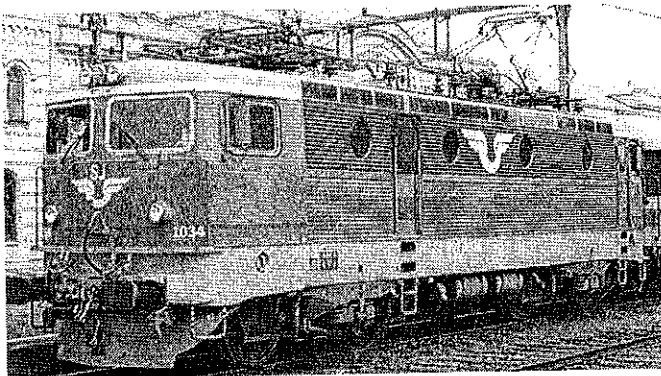
UA2G 2819 in Göteborg.

Kind	UA2	UA2G	UB2	Units
Maximum length	24400	24400	24400	mm
Wheelbase	2900+17700	2900+17700	2900+17700	mm
Driv. wheel diam.	880	880	880	mm
Seating cap. 1 kl	49	49	--	Person
Seating cap. 2 kl	---	--	76	Person
Weight in w.o.	52	52	54	Ton
Max. Speed	200	200	200	Km/h
Brake weight	75*	75*	75*	Ton

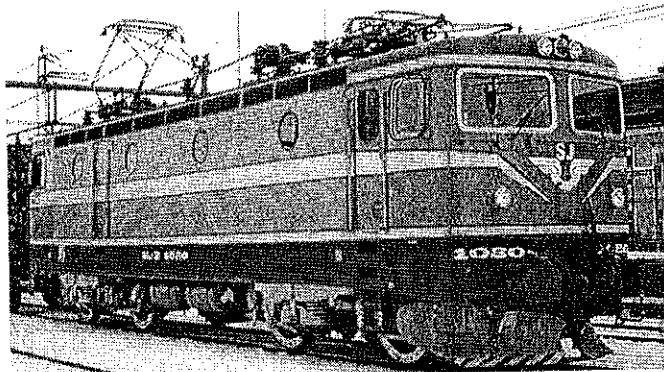
\* With magnet brakes + 36 ton.

### SJ RC

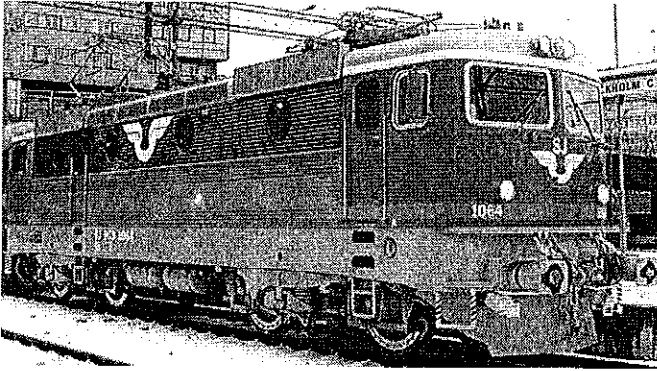
Normal train configuration is 1 locomotive and 2 – 13 car. There are 6 different kinds from the locomotive car, we will not go through all the details for them [SLM], they called RC1, RC2,...,RC6.



Rc2 1034 in Kistianstad.



Rc2 1080 in Falköping.

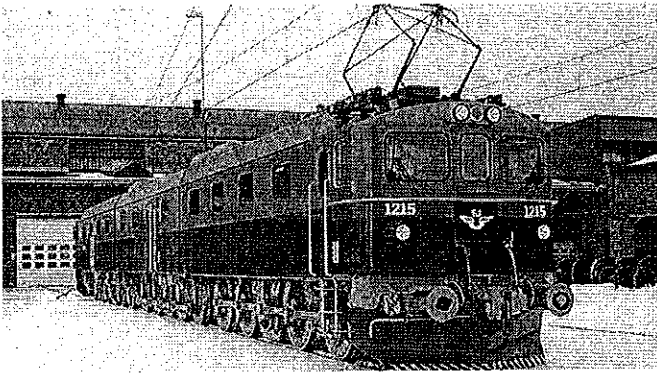


Rc3 1064 in Stockholm.

Type	Electrical bogie engine	
Axle succession	Bo'Bo'	
Effect	4 * 900=3600	Kw
Tract. Motor	Asea LJH108	
Motor Control	Low voltage	Voltage
Running steps	Step loose	
Transmission	Tube hole axel	
Max. length	15520	mm
Wheelbase for the locomotive	2700 - 7700	mm
Driv. wheel diam. for the locomotive	1300	mm
Weight in w.o. for the locomotive	78	Ton
Driv. wheel diam. for the car	980	mm
Weight in w.o. for the person and sleeping car	35 – 48	ton
Max. axle load	19.2	ton
Start. Trac. Effort	275	kN
Brake weight	85/87	ton
Max. Speed for RC1, 2, 4 and 5	130	Km/h
Max. Speed for RC3 and 6 (modern cars)	160	Km/h

#### SJ DM – DM3

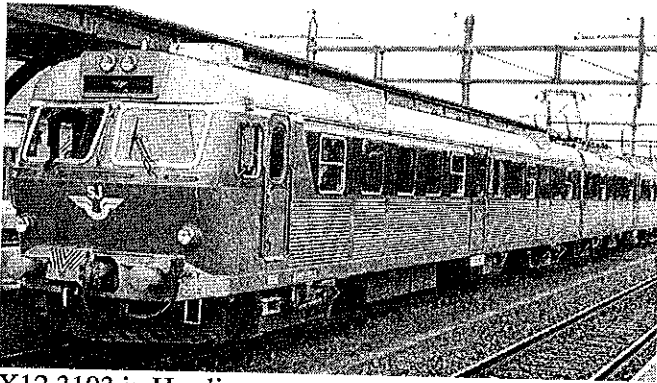
These trains are used for god's transportations of goods.



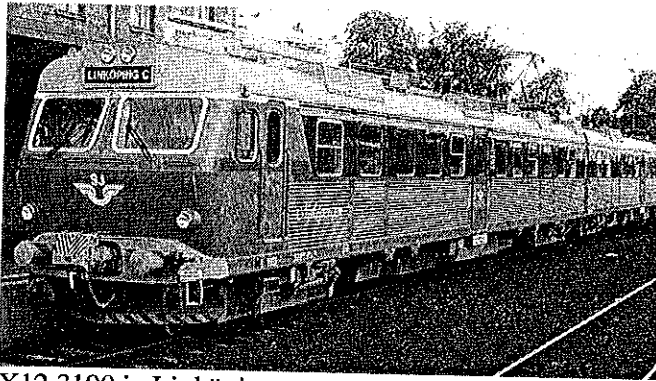
Locomotive Dm3		
Type	Electrical bogie engine	
Axle succession	1'D + D + D1'	
Effect	6 * 1200 = 7200	Kw
Tract. Motor	Asea KJD 137	
Motor Control	Low voltage	Voltage
Running steps	27 step	
Transmission	Lead pole	
Max. length for the locomotive	35250	mm
Wheelbase for the locomotive	31520	mm
Driv. wheel diam. for the locomotive	1530	mm
Max. length for the goods car	8400	mm
Weight in w.o.	270.0	ton
Adhes. Weight	240	ton
Max. axel load	20	ton
Start. Trac. Effort	280	kN
Brake weight	201/207	ton
Dynamic weight	385	Km/h
Pantograph	LLXJA135	
Max. Speed for RC3 and 6 (modern cars)	75	Km/h

X10, X12

This kind of trains known as local trains which consist most of the time of 2 cars only.



X12 3193 in Herrlunga.



X12 3190 in Linköping.

Type	X12A	X12B	X12	units
Axle succession	Bo'Bo'	2'2'	Bo'Bo'+2'2'	
Effect	4*320=1280	--	1280	KW
Tract. Motor	Asea LJM290-2		Asea LJM290-2	
Motor Control	Low voltage	--	Low voltage	
Running steps	Step loose	--	Step loose	
Transmission	Tube hole axel	--	Tube hole axel	
Maximum length	24934	24934	49868	mm
Wheelbase	2900+18000	2900+18000	45150	mm
Driv. wheel diam.	920	920	920	mm
Seating cap. 1 kl	--	24	24	Person
Seating cap. 2 kl	68	30	98**	Person
Weight in w.o.	60	40	100	ton
Adhes. Weight	60	--	60	ton
Max. Axel load	15	10	15	ton
Start. Trac. Effort	106	--	106	kN
Brake weight	90	57*	147*	ton
Dynamic weight	68	42	110	ton
Pantograph	FSFC,LSFC	--	FSFC,LSFC	
Max. Speed	160	160	160	Km/h

\* with magnet brakes + 19 ton.

\*\* plus 2 pull down seats

