APPENDIX A

LITERATURE REVIEW

In the literature review given in this appendix, problems due to the interaction between the vehicle and the track, various approaches to vehicle/track system modelling, and research with respect to track settlement is presented.

A.1 PROBLEMS DUE TO VEHICLE/TRACK INTERACTION

Most of the recent research on the dynamic behaviour of rail vehicles and the track has been stimulated by the need to understand the cause of practical problems arising from the interaction between the vehicle and the track and to develop solutions or treatments for those problems. Problems of vehicle/track interaction can be grouped into various areas of concern and are listed in Table A1 (Knothe and Grassie, 1993). The frequency range of particular interest for the different problems is also given.

Areas of primary concern to the present investigation are vehicle dynamics, bogies and unsprung mass, track ballast and track geometry. These issues are reviewed below.

Vehicle dynamics. The dynamic interaction between the vehicle and the track can cause problems with respect to the ride quality and the structural fatigue of the rail vehicle. In general, literature on the dynamic behaviour of rail vehicles is concerned with determining and evaluating ride quality (ORE Q C116 (Report 8), 1977; Parsons and Whitham, 1979). Hence, there are various ride quality standards available (Anon., 1961; ORE Q C116 (Report 8), 1977; Becker, 1978; Uetake, 1980; Yamazaki and Hara, 1980; Garg and Dukkipati, 1984; ISO 2631/1, 1985). In recent years the ISO 2631 standard (ISO 2631/1, 1985) is applied in most cases.

Table A1: Problems concerning vehicle/track interaction.

PROBLEMS OF VEHICLE/TRACK INTERACTION		
	Areas of concern	**Frequency range (Hz)**
1	Vehicles	0-20
2	Bogie and unsprung mass including wheel bearings, fatigue of axles, brake gear etc.	0-500
3	Irregular running surfaces of wheel and rail, due to wheel flats, out-of-round wheels, wheel corrugations, rail corrugations, dipped welds and joints, pitting and shelling	0-1500
4	Track components, that is fatigue of rail in bending, rail pads, concrete sleepers, ballast and track geometry	0-1500
5	Wheel/rail noise in terms of rolling noise, impact noise and squeal	0-5000
6	Structure borne noise and vibration	0-500

With respect to structural fatigue, a great deal of research has been done. Of interest are the more recent techniques that make use of an integrated design methodology to evaluate structural fatigue (Luo *et al.*,1994). These procedures make use of multibody simulation packages (Schielen, 1990; Kortüm and Sharp, 1993) to determine the dynamic loads acting through the suspension onto the vehicle structure. Measured track data is generally used as excitation input. Using a finite element model of the structural component on which the dynamic forces are acting, stress concentrations are identified and analysed. Stress histories are determined under simulated loading and the fatigue life is determined using an appropriate fatigue theory.

Bogie and unsprung mass. Vehicle suspensions are commonly designed to ensure that the rigid body modes of the bogie and the vehicle body occur below 10Hz. This is done to ensure adequate isolation of passengers or sensitive cargo from the vibrations coming from the track and to reduce the effective unsprung mass. Reducing the unsprung mass reduces the dynamic loads at the wheel/rail interface. At frequencies above 20Hz the suspension of the vehicle isolates all but the unsprung mass from the track input. According to Cox and Grassie (1986), the greater the unsprung mass, the greater is the peak contact force at low frequencies, but at high frequencies changing the unsprung mass has a negligible effect. Thus, in the frequency range between 10Hz and 50Hz, the wheelset becomes increasingly well isolated dynamically from the bogie. Problems which may be aggravated if not caused by the dynamic loading of the unsprung mass are for example fatigue of wheel bearings, brake gear, axle-hung traction motors and other bogie components. To control the effects of the unsprung mass it is thus important to prevent suspension devices, which rely on frictional damping, to "freeze up" (Frederick and Round, 1984).

Track ballast and geometry. Deterioration of ballast and the consequential loss of track geometry is an enduring concern of every railway system. According to literature, this problem occurs as a result of low frequency, high amplitude loading, as well as due to high frequency dynamic loading. In a paper by Frederick and Round (1984) it is suggested that if the damping in the suspension of a vehicle is insufficient to curtail the natural frequency response of the vehicle to the forced input from the track, significant deterioration of the track geometry would occur in wavelengths of approximately 9m. At these low frequencies the effects of the vehicle body and bogie frame dynamics need to be examined.

Research work with respect to issues of secondary importance to this investigation is summarised and listed below.

Wheel flats:

- Dong *et al.* (1994): Impact loads due to wheel flats are studied using a finite element model. The effects of varying system parameters on impact loads due to a wheel flat are investigated and presented.

Out-of-round wheels:

- Ahlbeck and Hadden (1985): The development and validation of a computer model for predicting impact loads due to wheel running-surface geometry errors is described.

Rail corrugations:

- Grassie (1980): The influence of vertical forces on the development of both long and short wavelength corrugations is investigated using mathematical models of the wheelset and the track in the frequency range from 100Hz to 1500Hz.
- Grassie *et al.* (1982): Two dynamic models of railway track are presented. These models include the effect of the rail pads and are used to calculate both the response of the track and the contact force between a moving wheel and the rail in the frequency range from 50Hz to 1500Hz. It is shown that the rail pad is of fundamental importance in the attenuation of dynamic loads in this frequency range.
- Clark (1984): Three corrugation theories are described to predict vibrations which reproduce observed wear patterns. Proposals for corrugation avoidance are put forward.
- Knothe and Ripke (1989): A model is used to investigate why surface irregularities of a certain wavelength grow in the corrugation initiation phase. The basic concept assumes a feed-back process between high frequency, transient vibrations and long-term wear processes.
- Ilias and Müller (1994): A semi-analytical method for the analysis of high frequency vibrations of the wheelset and railway track is presented and evaluated with respect to its applicability to technical problems such as the

calculation of corrugation growth rates.

- Hempelmann (1994): In this thesis a linear model for the prediction of short pitch rail corrugations is developed. It represents the formation of corrugation by a feedback between structural dynamics and a damage process.

Dipped welds and joints:

- Jenkins *et al.* (1974): This paper describes research work to understand the mechanisms and characteristics of vehicle/track forces. Particular attention is given to peak forces generated by dipped rail joints.
- Radford (1977): Radford investigated the vertical forces between a wheel and the rail at a dipped rail joint. A computer program is presented which uses continuously supported rail on a flexible foundation. A symmetric dipped rail joint is used, and some results are given. It was found that the first force peak occurs at a very high frequency (500-1000 Hz), corresponding to interactions in the wheel/rail contact zone. This force is believed to fatigue the rail but is not transmitted into the ballast. The second force peak is of greater duration and lower frequency (20-100 Hz). This force is transmitted to the ballast, causing track deflection and is believed to cause ballast compaction and deterioration in track geometry at the joint.
- Botwright (1979): This paper discusses measures taken to reduce impact forces and to minimise rail defects. Specific attention is given to joints in welded track.

Rail pads:

- Grassie (1989): Loading under traffic of concrete sleepers with a variety of resilient rail pads is examined using data from several field experiments. In all cases dynamic loads on sleepers were significantly reduced using the pads.

Concrete sleepers:

- Grassie and Cox (1985): The dynamic response of railway track with a section of unsupported sleepers is examined experimentally and a mathematical model of such track is presented. It is shown that in the absence of support, concrete sleepers are likely to crack if there are modest wheel or railhead irregularities.
- Ahlbeck and Hadden (1985): In this paper impact loads on concrete sleepers are measured and predicted. The sleeper model takes the first four bending

moments of the sleeper into consideration.

- Grassie (1993): The technique proposed in this paper for calculating the dynamic response of railway track to non-sinusoidal irregularities on the running surfaces of wheel and rail is used to emphasise that adequate attention has to be given to moments caused by dynamic loads during the design of a new sleeper.
- Maree (1993): Laboratory and field tests on resilient rail pads for the use on concrete sleepers are discussed. A theoretical model for determining pad and ballast stiffness and damping with receptance curves is discussed.

A.2 MODELLING OF THE VEHICLE/TRACK SYSTEM

Mathematical models of the dynamic behaviour of the vehicle/track system are particularly valuable to the railway engineer because they enable phenomena to be explored which cannot easily be measured, and effects of changes to the vehicle/track system to be examined without making costly and perhaps damaging modifications to the system. Despite the fact that modelling of the behaviour of track has been done for more than 100 years, its behaviour, particularly due to dynamic loading was not as clear as the dynamic behaviour of rail vehicles. This relative ignorance simply reflects the greater importance that was traditionally attached to problems of vehicle dynamics as against problems dealing with track dynamics and vehicle/track interaction.

Traditionally, railway operation authorities, as well as vehicle dynamicists for that matter, have considered the wheel-rail contact patch as the limit of their interests (Ahlbeck, 1995). The structure below the contact patch was only of concern to the track maintenance department, civil engineering and the so-called "dirt and rock" modellers. Contrary to this tradition, the vehicle and track form a single, complex dynamic system in which the dynamic response of the track forms a significant part of the vehicle "suspension system". The success of a railway system design depends on the prediction and understanding of the effects of both vehicle and track parameter variations due to ageing, wear, and degradation under service loads. The vehicle and the track thus form part of a complex feedback loop in which the dynamic loads generate changes in wheel and rail geometry and track response, which, in turn, result in higher loads. These load induced changes can affect vehicle ride quality, high speed stability, curving performance, vehicle and track maintenance, and operating safety.

The general objective in modelling the dynamic behaviour of the vehicle and the track is thus to reduce or contain the dynamic forces in the system. In 1959 Koffmann stated that a reduction in dynamic forces merits serious consideration. Spring and damper characteristics are matched to improve ride quality and reduce rail stresses. According to Koffmann, the dynamic wheel load depends on a number of factors such as track irregularity, sprung and unsprung mass, inertias and mass of the track, its stiffness, vehicle speed, as well as wheel diameter.

In the rest of this section a survey is given with respect to literature concerned with modelling the vehicle, rail, rail pad, sleeper, track foundation and finally the total vehicle/track system.

Vehicle model. The dynamic behaviour of the vehicle with respect to stability, steering and ride quality is most significant at low frequencies. This behaviour is understood adequately for most practical purposes, as is apparent from the fact that several software packages are commercially available to calculate the dynamic response of the vehicle. A comprehensive overview of these packages and some benchmarking results are given by Schielen (1990) and by Kortüm and Sharp (1993).

When using theoretical investigations to study the dynamic behaviour of a vehicle, criteria which affect the performance and the design of the railway vehicle have to be addressed. A review of some of the vehicle performance and design criteria is given by Newland and Cassidy (1975) and by Bhatti and Garg (1984).

Rail model. For static and stability analyses which were undertaken before 1960, the rail was considered to be a Bernoulli-beam (Winkler, 1867; Winkler, 1875; Timoshenko, 1926; Hetényi, 1946). Even now, it does indeed appear that this model is adequate for representing the response of the rail to vertical dynamic excitation for frequencies of less than 500 Hz (Grassie, 1993). However, such a model is no longer adequate for the response to vertical forces at higher frequencies as the shear deformation of the rail becomes increasingly important.

Rail pad model. In general, linearisation of the rail pads stiffness is justified. For vertical vibrations the pad is usually modelled as a spring and viscous dashpot in parallel. A model of the structural damping of the pad with a constant loss factor has also been used and is seen to be more consistent with the known behaviour of materials such as rubber (Knothe and Grassie, 1993).

Sleeper model. With respect to sleeper modelling two modelling theories are used; the Euler-Bernoulli theory and the Rayleigh-Timoshenko theory. The Rayleigh-Timoshenko theory is more accurate than the classic Euler-Bernoulli theory as it takes rotational inertia and shear deformation of the beam (sleeper) into account (Dahlberg *et al.*, 1993). The most complete sleeper model is a Timoshenko beam of variable thickness, which can be analysed using finite elements. Considerable success in correlating the calculated response of rail and sleepers in track to that measured at frequencies below about 700 Hz has been obtained by representing the sleeper as a uniform beam. In fact, it is known that the dynamic response to forces at the railhead is well represented up to 1kHz by modelling the sleeper simply as a rigid body.

To be able to predict crack development in sleepers under impact loads, Ahlbeck and Hadden (1985) have expanded existing vehicle/track interaction models. They developed and applied a validated seven degree-of-freedom nonlinear time-domain model. The response of track to high frequency excitation (50-1500 Hz) has also been analysed by Grassie *et al* (1982) to investigate short-pitch corrugations of rail.

In their paper Grassie *et al* present two new dynamic models, one continuous and the other incorporating the discrete mass of the sleepers. Rail pads were included in these models as they are of fundamental importance in the attenuation of dynamic loads in this frequency range.

Track foundation model. Through measurements it was found that the ballast generally deflects in a highly non-linear manner under load. In particular, there may be voids between sleepers and ballast, and the ballast itself may deflect nonlinearily (Esveld, 1989). Energy dissipation in the foundation occurs due to dry friction and wave radiation through the substrate. Despite this, most analyses use a simple two-parameter model in the vertical direction (Knothe and Grassie, 1993). A discrete sleeper support is used with the ballast being represented by a linear track stiffness and track damping. This model is justified if only the high-frequency dynamic behaviour is of interest and when the axle is close to the sleeper of interest. Loading and unloading when a bogie passes over a particular sleeper can be analysed approximately by such a linear model.

Other sleeper support models are discussed in a 'State-of-the-Art' paper by Knothe and Grassie (1993). There are in principle two different track support models, that is models with a completely continues support of the rail and those with a discrete support. Although a discrete support appears more representative of track laid on discrete sleepers, the corresponding continuous support is obtained by "smearing out" the discrete support along the track to get a continuous visco-elastic foundation and a continuous layer representing the sleepers. This continuous layer can model the sleepers as rigid bodies or as beams with distributed mass and stiffness. Continuous support models are valid for the calculation of the dynamic response of the track at frequencies below about 500 Hz for vertical excitation. A hierarchy of track models is also presented by Knothe and Grassie. The simplest representation of a continuous elastic foundation has been provided by Winkler in 1867. Winkler assumed the base to consist of closely spaced, independent linear springs. The only foundation constant is the foundation modulus. The most natural extension of the

Winkler model for homogeneous foundations is the Pasternak model where a second foundation constant, the "shear modulus", is also taken into consideration (Kerr, 1964; Dahlberg *et al.*, 1993).

The track structure can also be modelled as being of either finite or infinite in length. The type of structure is closely linked to the solution technique. Track structures of infinite length are commonly used for frequency-domain solutions whereas finite track structures are more appropriate for time-domain solutions.

Models of vehicle/track interaction. The individual sub-systems that form part of the total vehicle/track system are shown in Figure A1. Many similar models have been developed over the years (Zhai and Sun, 1993).

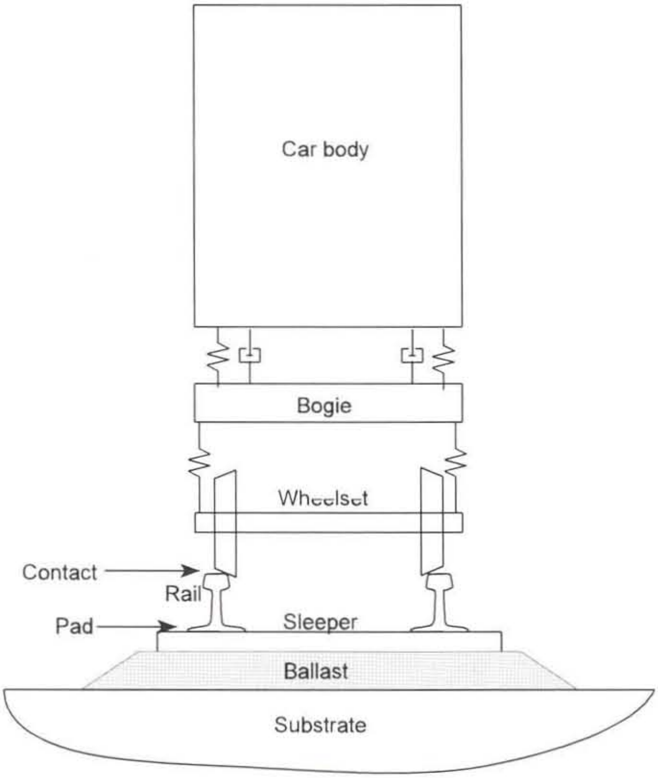

Figure A1: Components of the vehicle/track system.

To evaluate suspension features, Newland and Cassidy (1975) first considered the performance of a very simple single degree-of-freedom analytical model of the suspension system. In this model the mass of the bogie frame was neglected. Although the model yielded interesting data, it did not take account of bogie frame vibrations, which may lead to significant force transmission to the supported vehicle. Using a two-degree-of-freedom model the authors subsequently analysed fundamental design considerations as a function of a variety of track inputs.

The dynamic response of the vehicle/track system to non-sinusoidal irregularities was considered by Grassie (1993). Grassie showed that such calculations underestimate sleeper bending moments while overestimating the contact forces due to stiff and resilient rail pads. The model is used to assist in track design. Grassie's work also includes experimental measurements of the dynamic loads on the track. Irregular wheels are also used in the investigation. According to Grassie the dynamic load can be assumed to be 1.5 times the static load.

Another paper which is dedicated to the dynamic behaviour of the track and its foundation, is the paper by Girardi and Recchia (1991). They study the whole vehicle/track system as a unique mechanical system. The track foundation is modelled as a three-dimensional dissipation medium. Track and vehicle movements are modelled and solved using a classical finite element method.

In a paper by Nielsen (1994), the dynamic interaction between a perfectly round moving rigid wheel mass and an initially straight and non-corrugated continuous railway track is modelled. A parametric study to optimize the dynamic response of the track is done. The emphasis was to determine the maximum bending stress of the rail.

Basic theoretical models for the analysis of railway vehicles and tracks, and principle methods of their solution are also shown in a paper by Frýba (1987). The dynamic interactions between vehicle and track are emphasized and several basic equations are given to show the behaviour of their elements. Possibilities are described of how to simplify the theoretical models in order to obtain a simple solution.

A.3 TRACK SETTLEMENT

The repetitive dynamic loading and unloading of the track structures from train traffic causes inelastic deformations in the ballast and the underlying foundation. As the traffic accumulates these deformations develop to a point where maintenance is required to restore the required vertical space curve of the track. Subsequently the deformation process starts again. A chronological overview of some of the papers that discuss this issue is given in this section.

A report released by the International Union of Railways' Office for Research and Experiments (ORE Q D71 (Report 10), 1970) describes laboratory and field studies aimed at discovering the fundamental laws describing the response of the ballast layer to repetitive loads. Studies were made by both British Rail and Nederlandse Spoorwegen research teams. The main conclusions were, that ballast becomes more stable, that is the rate of track settlement decreases as the number of load applications increases. Furthermore it was found that the settlement of the ballast is dependent upon the degree of initial ballast compaction. It was found that the use of on-line tamping machines for re-levelling the track, disturbs the underlying ballast only to be followed by a restart of the ballast deformation cycle.

In another research report (ORE Q D117 (Report 5), 1974), results of a series of triaxial tests on dry limestone ballast under repeated axial loading are described. It was found that the deformation of the ballast is proportional to the logarithm of the number of load cycles and proportional to the superimposed axial stress raised to an exponent between 1 and 3. The axial stress was found to depend mainly on the largest load when two load levels were applied. It was also observed that the axial stress reduced when full load removal did not occur between load cycles.

In 1982, Selig and Alva-Hurtado presented a methodology to calculate track settlement for maintenance cycle prediction. To analyse the stress state in the sub-structure of the track under vertical wheel loading, they used the three-dimensional elastic multi-layer computer model GEOTRACK (Chang *et al.*, 1980). Permanent strain behaviour was determined and integrated to estimate track settlement. The methodology described, provides a tool for predicting the elastic and permanent deformation behaviour of railway track systems and takes a variety of factors influencing the deformation behaviour into account. Factors taken into consideration are axle load, number of load cycles, rail and sleeper characteristics, and the properties and thickness of the ballast and underlying layers. According to Selig and Alva-Hurtado there is no general constitutive law available to account for the effect of cyclic loading in ballast and subgrade materials.

In another paper by Stewart and Selig (1982), the previous methodology is further described and the prediction of stresses and deformations that develop in the track due to residual horizontal stresses in the ballast, and due to the effects of shear stress reversal on the resilient modulus of the ballast is presented. A method to predict the strains in the ballast due to mixed wheel loads is also presented.

The paper by Leshchinsky *et al* (1982) presents a different simplified methodology for evaluating the effect of varying loads on the subgrade while also considering the non-linear properties of the substructure. A definition of a so-called "damage factor" is given. The damage factor is defined as the ratio of permanent settlement under heavier axle load to the permanent settlement under an existing axle load. A two-step technique is proposed. Firstly, the sleeper reaction has to be determined using a beam on elastic foundation model. Then the stress distribution can be calculated to evaluate the subgrade performance. After calculating the sleeper reaction due to an applied force, it is possible to determine the reaction of a sleeper away from the applied load. This makes it possible to use the method of superposition to determine the sleeper load due to several axles in the adjacent area.

The deterioration of the vertical track profile was also investigated by Lane (1982) using a computer model to calculate the deterioration of the track. Static and dynamic sleeper-ballast forces were predicted. Two models were used; one for localised discrete irregularities and the other for extended spatially distributed irregularities. In the extended irregularity model a Gaussian distribution of the ballast properties in terms of ballast stiffness was used. Ballast settlement properties were determined experimentally and calculations showed how the roughness of the track depends on both track and vehicle parameters.

In 1985, Shenton studied the deterioration of the vertical track geometry. Factors influencing the deterioration of the track were examined using a computer model which simulates the deterioration of the track due to various factors. The paper identifies six possible causes of track deterioration. They are, dynamic forces, rail shape, sleeper spacing, sleeper support, ballast settlement, and the substructure. These mechanisms can all take place simultaneously and are often interactive. Shenton described the quality of the track over a 200m section by the standard deviation of the vertical track profile. The deterioration under traffic was found to be a function of track quality. Observations over many kilometres of track lead to the conclusion that in general good track remains good and poor track remains poor throughout a period of many maintenance cycles. The number of tamping operations seem to have very little influence. It is concluded that the track has an inherent quality which is determined during the early part of its life in terms of the quality of track components, track foundation and work done during installation.

In a report released by the Office for Research and Experiments (ORE Q D161 (Report 1), 1987), historical data from work done by previous ORE Specialist Committees is analysed and the main factors influencing the deterioration of the track geometry are discussed. The relationship between the deterioration of the track geometry and the traffic carried is shown, but it was impossible to establishing laws relating to different traffic and track conditions. It was also found impossible to statistically differentiate between the effect of traffic, track construction and foundation on the rate of track deterioration. Consequently further experimental research was recommended to obtain a better understanding of the discrete causes that lead to the deterioration of track geometry.

In 1989 Schwab and Mauer simulated the track settlement behaviour under dynamic loading conditions using an interactive algorithm comprising of three model components. The components consisted of a dynamic vertical vehicle model, a discrete finite element track model, and a mathematical model for the track settlement based on the settlement algorithm derived by Hettler (1984). Simulations of track settlement under various rail and track geometry errors are described and simulated results are discussed.

Extensive research work on elastic ballast deflection and settlement was also presented by Eisenmann *et al* (1993). By means of a power rule, which is in line with other European research work (ORE Q D71 (Report 10), 1970; ORE Q D117 (Report 5), 1974; ORE Q D161 (Report 1), 1987), the deterioration of the track was established on the basis of the prevailing ballast pressure.

In recent times more emphasis is being placed on efficient track maintenance. Using a variety of old or new track settlement equations and track settlement prediction models a mechanistic method to schedule track maintenance is combined with an economic model to determine the life cycle cost of maintenance alternatives. Chrismer and Selig (1993) for example used information on track and ballast conditions, together with a specific maintenance strategy, to calculate and relate the settlement of ballast, sub-ballast, and subgrade to differential settlement limits. Riessberger and Wenty (1993) state that track quality is the key to improved load bearing capacity and efficient maintenance. In their paper both practical experience and theoretical considerations are used to maintain the required load bearing capacity of the track and maintain excellent track quality under high axle load or high speed operating conditions. Machine systems for economical track maintenance are also considered.