KTH Engineering Sciences

Railway Track Stiffness

Dynamic Measurements and Evaluation for Efficient Maintenance

by

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Doctoral Thesis

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Preface

After many years of national track stiffness measurements at standstill condition, Banverket (Swedish Rail Administration) participated in the EU-financed Eurobalt II project. Mr Björn Dehlbom, Mr Åke Jahlénius and Mr Jan Köhler of Banverket had a vision of continuous stiffness measurements along the track and worked hard to make this part of the project, the prototype trolley, a success during 1998 – 2000. During these years I learned a lot about measurement and evaluation techniques. After a few years of consolidation and more measurements, a joint research project called "Track stiffness - new measurement and evaluation techniques for improved track performance" (SAMBA 7, where SAMBA is a Swedish acronym for vehicle-track interaction) started at the Royal Institute of Technology (KTH), Division of Rail Vehicles. The participants were Banverket head office (now Operation Division) where I am employed, Banverket Production Measurement Unit (which has built the new measurement vehicle) and KTH. The aim of this project was to improve current measurement and evaluation techniques in the area of vertical track stiffness, and show relations between track stiffness and degradation/maintenance of the track.

The research presented in this thesis has involved many persons to whom I'm grateful. Mr Åke Jahlénius at Banverket Production (who is the inventor of the basic measurement principles) and Mr Bengt-Erik Bengtsson at ZETA Instrument have been invaluable in all aspects of measurements. Without the hard work by Mr Jan Gomersson and his staff at Banverket Production the Rolling Stiffness Measurement Vehicle (RSMV) would never had been ready in time. Thank you also for all long nights of field measurements.

My supervisor at KTH, Professor Mats Berg, has with a warm and welcoming atmosphere guided me through these years of research. All discussions in the reference group have also been very valuable.

Since I'm not myself a geotechnician, discussions, explanations and support from Mr Alexander Smekal and Ms Eva-Lotta Olsson at Banverket are gratefully acknowledged. Also the support from Mr Björn Dehlbom at Ramböll and Professor Anders Bodare at KTH is appreciated.

I'm deeply grateful to my former superiors Mr Bertil Eriksson and Mr Björn Paulsson (who has had great importance for the growth of Swedish railway research) for giving me the opportunity and funding for this research project. Ms Eva Emilsson and Mr Tomas Ramstedt, my superiors in the new organisation of Banverket, have also generously allowed me time and resources to finalize the thesis. I also like to thank my colleagues at the Section of Track and Civil Engineering at Banverket for a friendly and inspiring environment, especially Tech. Lic. Jan Spännar and Dr Martin Li for all usable suggestions. After my licentiate degree the thesis work has been financed through the European research project Innotrack, which is highly acknowledged.

Mr Ingemar Persson at DEsolver and Dr Amir Kaynia at Norwegian Geotechnical Institute (NGI) have guided me through the simulation programmes necessary in the project. Dr Michael Burrow at University of Birmingham helped me improving the language in chapter 4. Discussions with Mr Ted Stephens and Mr Andrew Smith at Bentley Systems on analysis for track maintenance management are gratefully appreciated.

My beloved family; Hanna, Vera, Stina and our future junior – you are my everything.

Eric Berggren, Borlänge, April 2009, S.D.G.

Abstract

Railway track stiffness (vertical track load divided by track deflection) is a basic parameter of track design which influences the bearing capacity, the dynamic behaviour of passing vehicles and, in particular, track geometry quality and the life of track components. Track stiffness is a broad topic and in this thesis some aspects are treated comprehensively. In the introduction part of the thesis, track stiffness and track stiffness measurements are put in their proper context of track maintenance and condition assessment.

The first aspect is *measurement* of track stiffness. During the course of this project, Banverket has developed a new device for measurement of dynamic track stiffness called RSMV (Rolling Stiffness Measurement Vehicle). The RSMV is capable of exciting the track dynamically through two oscillating masses above one wheelset. The dynamic stiffness is a complex-valued quantity where magnitude is the direct relation between applied load and deflection (kN/mm) and phase is a measure of deflection-delay by comparison with force. The phase has partial relationship with damping properties and ground vibration. The RSMV repeatability is convincing and both overall measurements at higher speeds (up to 50 km/h) and detailed investigations (below 10 km/h) can be performed. The measurement system development is described in Paper A and B.

The second aspect is *evaluation* of track stiffness measurements along the track from a track engineering perspective. Actual values of stiffness as well as variations along the track are important, but cannot always answer maintenance and design related questions alone. In Paper D track stiffness is studied in combination with measurements of track geometry quality (longitudinal level) and ground penetrating radar (GPR). The different measurements are complementary and a more reliable condition assessment is possible by the combined analysis. The relation between soft soils and dynamic track stiffness measurements is studied in Paper C. Soft soils are easily found and quantified by stiffness measurements, in particular if the soft layer is in the upper part of the substructure. There are also possibilities to directly relate substructure properties to track stiffness measurements. Environmental vibrations are often related to soft soils and partly covered in Paper C. One explanation of the excitation mechanism of train induced environmental vibrations is short waved irregular support conditions. This is described in Paper E, where track stiffness was evinced to have normal variations of 2 – 10 % between adjacent sleepers and variations up to 30 % were found. An indicative way of finding irregular support conditions is by means of filtering longitudinal level, which is also described in the paper. Train-track interaction simulation is used in Paper H to study track stiffness influence on track performance. Various parameters of track performance are considered, e.g. rail sectional moment, rail displacement, forces at wheel-rail interface and on sleepers, and vehicle accelerations. Determining optimal track stiffness from an engineering perspective is an important task as it impacts all listed parameters.

The third aspect, *efficient maintenance*, is only partially covered. As track stiffness relates to other condition data when studied from a maintenance perspective, vertical geometrical defects (longitudinal level and corrugation/roughness) are studied in paper F. The general magnitude dependency of wavelength is revealed and ways of handling this in condition assessment are proposed. Also a methodology for automated analysis of a large set of condition data is proposed in Paper G. A case study where dynamic track stiffness, longitudinal level and ground penetrating radar are considered manifests the importance of track stiffness measurements, particularly for soil/embankment related issues.

Keywords: Railway track stiffness, maintenance, soil dynamics, measurement, simulation, vibration

Outline of Thesis

The scope of this thesis is measurements of railway track stiffness and how to use the results for efficient maintenance. The thesis starts with an introductory part which gives the relevant basis of track degradation and maintenance as well as track stiffness and track stiffness measurements. The introduction is followed by eight appended papers:

A   Berggren E, Jahlénius Å and Bengtsson B-E: *Continuous Track Stiffness Measurement - An Effective Method to Investigate the Structural Conditions of the Track*, Proceedings of the conference Railway Engineering - 2002, London, 3-4 July, 2002. ISBN: 0-947644-49-0

B   Berggren E, Jahlénius Å, Bengtsson B-E and Berg M: *Simulation, Development and Field Testing of a Track Stiffness Measurement Vehicle*, Proceedings of 8th International Heavy Haul Conference, Rio de Janeiro, 13-16 June, 2005. ISBN: 0-646-33463-8

C   Berggren E, Kaynia A and Dehlbom B: *Identification of Substructure Properties of Railway Tracks by Dynamic Stiffness Measurements and Simulations*, resubmitted to Journal of Sound and Vibration.

D   Smekal A, Berggren E and Silvast M: *Monitoring and Substructure Condition Assessment of Existing Railway Lines for Upgrading to Higher Axle Loads and Speeds*, Proceedings of 7th World Congress on Railway Research, Montreal, 5-7 June, 2006.

E   Berggren E: *Measurements of Track Stiffness and Track Irregularities to Detect Short Waved Support Conditions*, Proceedings of International Conference on Railway Track Foundations, Birmingham, 11-13 September, 2006. ISBN: 0-704426-00-5

F   Berggren E, Li M and Spännar J: *A New Approach to the Analysis and Presentation of Vertical Track Geometry Quality and Rail Roughness*, Proceedings of 7th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems (CM2006), Brisbane, 24-27 September, 2006. Also in journal of WEAR, Vol 265, pp 1488-1496, 2008.

G   Berggren E: *Efficient Track Maintenance - Methodology for Combined Analysis of Condition Data*, submitted to the conference IHHA 2009. Candidate paper to Special Issue of Journal of Rail and Rapid Transit.

H   Li M and Berggren E: *A Study of the Effect of Global Track Stiffness and its Variations on Track Performance: Simulation and Measurement,* submitted to the conference IHHA 2009. Candidate paper to Special Issue of Journal of Rail and Rapid Transit.

Author contribution of papers

For all the papers Eric Berggren planned, led and performed the measurements by Banverket (together with the measurement unit of Banverket Production), and also performed the signal processing and the evaluations.

Paper A and B, that describe the measurement principles were written and presented by Berggren. The co-authors Jahlénius and Bengtsson designed and led the mechanical construction of the prototype trolley and the RSMV as well as the measurement systems. Simulations in Paper B were performed by Berggren (with help from Ingemar Persson at DEsolver) under supervision of Berg. Berg and Alexander Smekal reviewed the papers. Paper B was awarded a Best Paper Award at the IHHA conference in Rio de Janeiro.

In **Paper C,** Berggren performed the simulations and wrote the paper except section 2.1 that was written by Kaynia. The geotechnical investigations including GPR measurements were planned and led by Dehlbom who also helped with the evaluation of results.

Smekal presented **Paper D**. Berggren wrote the sections about track geometry quality and stiffness while Silvast wrote the section describing GPR measurements. Introduction, case study and conclusions were written in co-operation by all authors.

Berggren is the sole author of **Paper E and G** and all work adherent with these papers was naturally executed by Berggren.

Paper F was presented by Berggren who also wrote the parts describing track geometry quality and conversion of the physical model with system identification techniques. Li wrote the section of train-track interaction and Spännar the part describing corrugation/roughness measurements. The remaining sections (introduction, analysis, results, and conclusions) were written in co-operation by all authors.

Finally, **Paper H** was written and will be presented by Li, except the section of stiffness measurements and statistics that was written by Berggren.

Besides the papers in this thesis, publications written in this research project are listed below. Due to overlap or subject outside the core of the thesis, these are formally not part of the thesis.

Smekal A. and Berggren E., Mitigation of Track Vibration at Ledsgård Sweden - Field Measurements Before and After Soil Improvement. Proceedings of the conference Eurodyn 2002, Munich, 2-5 September, 2002.

Smekal A., Berggren E. and Hrubec K., Track-Substructure Investigations using Ground Penetrating Radar and Track Loading Vehicle. Proceedings of the conference Railway Engineering - 2003, London, 30 April - 1 May, 2003.

Berggren E., Dynamic Track Stiffness Measurement – A New Tool for Condition Monitoring of Track Substructure, Licentiate Thesis TRITA AVE 2005:14, Royal Institute of Technology (KTH), Stockholm 2005.

Berggren E., The role of vertical track stiffness measurements in condition based maintenance of railway tracks – A pilot study, Report TRITA AVE 2005:31, Royal Institute of Technology (KTH), Stockholm 2005.

Li M., Berggren E. and Berg M., Assessment of Vertical Track Geometry Quality based on Simulations of Dynamic Track-Vehicle Interaction, Proceedings of 9th International Heavy Haul Conference, Kiruna, June, 2007. Also in Proc. IMechE, Part F: J. Rail and Rapid Transit, 2009, 223 (F2), 131-139.

Li M., Berggren E., Berg M. and Persson I., Assessing of Track Geometry Quality based on Wavelength Spectra and Track-Vehicle Dynamic Interaction, Proceedings of 20th International Symposium on Dynamics of Vehicles on Roads and Tracks, Berkeley, 13-17 August, 2007. Also in Vehicle System Dynamics, Volume 46, Supplement, September 2008 , pp. 261-276.

Berggren E., Vertical Track Stiffness Measurements - A Literature Review for the REVA project at Cenit, Barcelona, 2007.

Burrow M., Teixeira P., Dahlberg T., Berggren E., Track Stiffness Considerations for High Speed Railway Lines, to appear in the book N. P. Scott (ed.), Railway Transportation: Policies, Technology and Perspectives, Nova Publishers, in print.

Berggren E., A Novel Approach for Whitening of Versine Track Geometry, to be presented at the IAVSD symposium, Stockholm, 17-21 August 2009. Paper to appear on the symposium CD.

Contribution of Thesis

There exists some devices for rolling track stiffness measurements worldwide but none of these methods, except the method presented in this thesis and the French portancemetre [31], measure the *dynamic* stiffness. The measurement technique and partly the interpretation of the results are therefore the main contributions of this thesis.

In more detail the thesis contribution can be summarized as:

- Proposal of a new method and vehicle, called RSMV (Rolling Stiffness Measurement Vehicle), for continuously measuring the dynamic vertical track stiffness.

- Dynamic excitation through an ordinary wheelset with the help of oscillating masses. However, there exists a similar system for road testing [64].

- Possibility to excite the track with arbitrary sinusoidal frequencies between 3 and 50 Hz while rolling and calculate corresponding dynamic track stiffness.

- Possibility to excite the track with arbitrary noise frequencies between 3 and 50 Hz while rolling and calculate corresponding dynamic track stiffness as a function of both spatial position and frequency.

- Presentation of dynamic track stiffness magnitude and phase as 2-D surfaces where resonance phenomena and changing dynamic behaviour along the track can easily be detected.

- Investigation by simulation of soft soil dynamic properties at low frequencies and a methodology of how to interpret measured dynamic properties from the RSMV into properties of the soft soil track.

- Comparisons and connections between dynamic track stiffness and geotechnical properties of the track in a number of case studies.

- New insights into the magnitude dependency of wavelength for vertical track irregularities.

- Methodology of how to automate evaluation of condition data to find root causes of problem sites.

- Average and standard deviation values of track stiffness for longer parts of track are for the first time published.

- Use of measured track stiffness variations along the track in train-track interaction simulations for results more in comparison with reality.

1 INTRODUCTION

Knowledge about the condition of railway tracks is vital in performing optimal track maintenance. This knowledge is gathered with the help of inspections as well as manual and automatic measurements. Most of the imperfections of a track are visible as such rail defects and track geometry irregularities. Therefore, the most important inspections are ultrasonic testing for the rail, and track geometry measurements for the track. To be able to determine the root cause of a problem or to conclude how changed traffic conditions will affect the track, more measurements or visual inspections are needed. An introduction to track maintenance and different measurements can be found in the text books of Esveld [24] and Selig and Waters [55].

A railway track structure can be divided in superstructure and substructure. According to [55] the superstructure consists of rails, fastening system and sleepers, while the substructure consists of ballast, subballast, embankment fill (if needed for topography) and subsoil. Since many of the possible problems with the substructure are connected to water, also the drainage system is a part of the substructure. There are also other divisions used; sometimes the ballast is classified as part of the superstructure and sometimes the subsoil is classified as a separate part besides super- and substructure. Old tracks have very often not sufficient thickness of ballast, no pure drainage and no subballast layer.

Historically, most attention has been paid to inspection techniques of the superstructure. Several of such techniques are standard measurements used worldwide. The substructure has been given much less consideration, especially the subballast and subsoil components, even though it has a major influence on the cost of track maintenance [55]. Most of the substructure investigation techniques are not standard measurements and are not performed as regular measurements. This thesis focuses on a new condition monitoring technique for the substructure: Dynamic vertical track stiffness measurements along the track.

Track stiffness is the relation between applied force and displacement response of the rails. The track stiffness varies both with frequency, dynamic amplitude, applied preload and position along the track. Track stiffness is an important interaction parameter in the wheel-rail contact, and variations of track stiffness as well as extreme values (both low and high) will affect the degradation of the track. Track stiffness can be measured both at standstill and while rolling along the track. There are some different approaches to rolling measurements, all with different advantages/disadvantages. Very few railway authorities have access to track stiffness measurement equipment. The method proposed in this thesis for rolling measurements uses dynamic excitation of the track through a standard vehicle wheelset, and can therefore investigate dynamic properties of railway track without any severe restrictions.

2 TRACK DETERIORATION

A railway track will not improve its condition without maintenance (though there are rare special cases as for example freezing-thawing where parts of the cycle may include an improved condition). The process of declined condition is called deterioration. The mechanisms of how the track deteriorates due to different conditions in traffic and climate are rather complex. There are numerous models that describe track deterioration and a compilation can be found in [28] and [79]. There are rather different processes that cause deterioration of the different parts in the railway structure. Rail deterioration is often described by wear and fatigue, while track geometry quality deterioration is related to e.g. settlements of ballast and soil.

2.1 Driving forces of deterioration

In some cases, the track can deteriorate without any traffic (e.g. the soil may settle due to the weight of the embankment, especially in the early years after construction) but in most cases passing traffic is the driving force of deterioration. A railway track is designed to distribute the loads from trains all the way from the high pressure of steel to steel contact (up to 1 GPa) down to the soil/ground (some tens kPa). The way the load is distributed through super- and substructure is a matter of original design and current condition. Stiffness of different components in the track structure, as well as the resulting (global) track stiffness will partly determine how the loads are distributed.

Track forces consist of static, quasi-static and dynamic contributions and all are important for track degradation. In the following, some aspects determining forces and thereby influence degradation are listed.

Vehicle characteristics
The vehicle characteristics such as speed, axle load, unsprung mass, suspension, wheel profile, axle spacings etc influence all aspects (static, quasi-static, and dynamic) of track forces. The current condition of the wheel such as wheel flats and wheel corrugation will contribute to dynamic forces.

Track characteristics
Track design geometry (curves etc.) influences static and quasi-static forces, while track geometry quality is a main contributor to dynamic forces. Corrugation, often called rail roughness will generate high-frequency forces whereas rail imperfections such as joints or poor welds lead to impact forces.

Deterioration processes in brief
The main processes of track deterioration are wear, fatigue and settlement. The rail experience wear and fatigue. Rail deterioration is often a complicated relation between vehicle characteristics, creepage in the wheel-rail contact and other factors [19]. Additionally, the deterioration is highly non-linear. Rail wear is for example sometimes described by wear maps where a small change in conditions may totally change the rate of wear. Deterioration by Rolling Contact Fatigue (RCF) is in many cases important and also safety-related as RCF initiates cracks that will grow by time and traffic, possibly leading to a rail break.

Pads, clips, and sleepers have all deterioration processes of their own dependent of which forces, bending moments etc. that expose them.

The ballast and sub-ballast layers comprehend differential settlement due to stone reorientation. This also leads to wear of the stones. Fines produced by this wear together with possible other material is called ballast fouling, entailing decreased drainage conditions. The soil may be exposed to settlement. When the settlement varies along the track resulting in differential settlements, these are directly visible as track geometry quality variations.

2.2   Track stiffness and deterioration

Global track stiffness is a combination of stiffnesses of all different layers and components. The way local stiffnesses are combined determines in turn the displacements of each layer. Forces and displacements will together with support conditions determine bending moments.

A rail on a low global stiffness track will experience large displacements and large bending moments, which will influence long-term fatigue conditions. As the rail displacements are large, more sleepers will be involved sharing the load leading to lower forces on sleepers. Dynamic train-track interaction forces will be relatively low. Contrary, a rail on a high global stiffness track will experience small displacement and small bending moments. However, fewer sleepers will share the load increasing forces for each sleeper. Also dynamic train-track interaction forces will be relatively higher. Calculations showing these principles can be found in Paper H.

Ballast and sub-layers are influenced both by stiffnesses above and under themselves. A ballast layer resting on bedrock will experience large internal compression/expansion during a train-passage as compared to a ballast layer resting on a soft clay layer. The endurance of the two cases will be significant if only this aspect is considered.

Differential settlements in the ballast layer is more loosely connected with stiffness and more with compaction and variations in sleeper support (which yet may be detected by stiffness measurement, see Paper E). Settlements of lower layers and soil are also more loosely connected with stiffness. Two soil layers can have the same stiffness, but totally different ability for settlements. Yet, very soft layers, such as clay and peat, have generally close correlation between stiffness and settlements.

3   TRACK MAINTENANCE

Railway lines are investments with very long life. Today many tracks are over 100 years old. Of course components have been exchanged during the years, but parts of the track might remain the same – especially the substructure. Typical lifetimes of for example rails are 30 – 60 years and turnouts 20 – 30 years [65]. However, to ensure this long life a large amount of maintenance is necessary.

A significant part of a railway infrastructure owner's budget will be devoted to maintenance. For instance, in the year 2007 track maintenance in Sweden cost 149 SEK per metre on an average for the whole network. For the tracks with most intense traffic, the same figure was 881 SEK per metre [4]. If reinvestments are included the figures are 227 and 1114 SEK per metre respectively. See also [2] and [80].

There are several, quite obvious reasons for maintenance, for example:
- **Safety** – Probability for accidents needs to be low.
- **Comfort** – Comfort is important, both for passengers and freight as well as for the environment in terms of noise and vibration.
- **Availability** – With lots of failures and speed restrictions due to safety etc. the availability of the track will be low.
- **Economy** – A track with low quality is cost driving, since the deterioration of both track and trains will be higher. At the same time maintenance is expensive. Optimisation and Life Cycle Cost (LCC) planning is needed.

Since many railway tracks are quite old, the demands put on the tracks today are different from the ones when the tracks were built. There is a clear trend towards higher speeds and higher capacity (more trains on the tracks and heavier trains). To face the new circumstances, more effort has to be put on track maintenance to ensure the issues of safety, comfort, availability and economy. Nowadays more trains occupy the track and the competition with other means of transportation becomes harder. Therefore there is also a trend towards decreased time for maintenance and decreased funds for maintenance.

The number one solution for optimal maintenance is to do the right measure at the right time to fulfil the requirements of safety, comfort and availability in terms of LCC. This task is virtually impossible, since it requires complete knowledge about the current condition of the track and what effect different kinds of maintenance, or no maintenance, will have on the track. Instead, the goal of condition based maintenance is to come as close to this optimum as possible. This is done with the help of measurements of important parameters which are analyzed to give knowledge about the condition of the track. After that, regulations, budget constraints and knowledge about the deterioration (from models and/or skilled engineers) are used to make decisions about maintenance.

The track maintenance part of the LCC is often similar, or larger, than the building cost [65]. Even figures of up to 70 % are mentioned in the literature [17]. Figure 1 illustrates the LCC of a track in principle, and to what extent it is possible to influence the LCC.
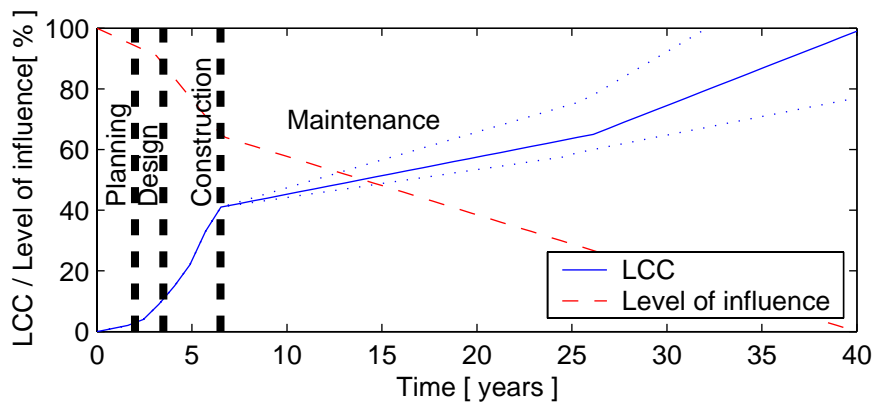
4

Figure 1. Different parts of LCC and possible influence on the LCC
during the life of a railway line [65].

Of course, the track could be maintained in different ways. This is also indicated in the figure by the dotted lines. Good/optimal maintenance can add life to the track, saving lots of money.

Since such a large part of a railway authority's budget is spent on maintenance, it is of vital importance to have a clear maintenance strategy. Otherwise suboptimal maintenance will be likely with a high degree of ad hoc maintenance (fire fighting) and run to failure. Proactive maintenance will in most cases be a better solution than reactive maintenance, provided it is done with correct timing. A maintenance strategy can also include scheduled activities such as tamping, component replacement, grinding etc (proactive maintenance). This is quite common [24], but is also suboptimal if not a large part of the track in question is in need of the maintenance operation. One strong argument for scheduled maintenance is safety. Most literature suggests condition based maintenance as the number one maintenance strategy [1], [17], [18], [35], [57]. One definition of condition based maintenance is: Proactive maintenance based on frequent inspection/measurement of the condition of the track. Actions are not taken until the degradation comes close to a non-acceptable condition [65].

As optimal maintenance is dependent on a large amount of information, there is a huge need for assistance. UIC made some pioneering work developing ECOTRACK [22] in the early 1990s. However, few railways run such systems on a regular basis. The delay for incorporating such systems has mainly been disorder of data, lack of databases, and capacity problems of storage and computers. Today there are no technical problems although some railways may still suffer from disorder of data. The emerging markets for such systems are large, as the benefit exceeds the investment by far. Banverket is currently implementing the software Optram as an aid for maintenance decisions.

To perform optimal condition based maintenance, also the condition of the substructure has to be known. This thesis certainly aims at improving this knowledge. An extensive introduction to the substructure of railway tracks can be found in [55]. A brief introduction to the measurement techniques for the railway substructure can be found in [24]. An introduction to railway subsoil problems can be found in [40].

5

3.1   Measurements related to the substructure

In this section, only the most important measurement methods related to track stiffness measurements (which are described in the next chapter) are described.

Measurement of track geometry quality is one of the key parameters for condition assessment of railway tracks. A substructure problem is often first discovered by the track irregularities. Large irregularities will give rise to poor ride comfort in the trains and higher dynamic forces between rail and wheel which results in faster degradation. Even larger irregularities become a safety problem with certain derailment risk. As an example, track irregularities of the main lines in Sweden are measured 6 times a year.

Ground Penetrating Radar (GPR) is based on transmission of very short electromagnetic impulses which are reflected from the interfaces of materials of different dielectric properties [33]. The transmitted impulses are of high frequency (10 – 2000 MHz), lasting maximum 10 ns. With the help of GPR it is possible to get information about different layers and their depth. Also disturbed layers (mixture between two layers) can be detected. The use of GPR has been limited due to problems, mainly with steel in the superstructure (rails and reinforced concrete sleepers) which disturbed the measurements. However, during the last years this has been solved, and today there are several companies performing such measurements. Some of the current research on GPR for railways involves detecting fouled ballast from a frequency analysis of the electromagnetic responses [59]. A measurement with both track stiffness and GPR is presented in Paper D. Combined analysis of track stiffness, GPR and longitudinal level is described in Paper G.

There exists a wide variety of site investigation techniques, ranging from non-destructive geophysical methods like spectral analysis of surface waves (SASW) to traditional geotechnical investigations and laboratory testing. All investigation techniques aim at determining physical parameters of the substructure, like shear strength, modulus, pore water pressure, moisture content, shear wave velocity etc. An introduction to different kinds of techniques can be found in [55] and [13]. The main advantage compared to continuous methods is that very detailed knowledge can be obtained, and the main disadvantage is that the knowledge is very local and site investigations are often time consuming.

3.2   Maintenance methods related to the substructure

There are several different methods for maintenance depending on the current condition of the track, and what part of the track that is in need of maintenance.

Tamping

Tamping is the common term for the operations of lining, levelling and tamping, since it is performed by the same machine. The tamping machine corrects the track geometry and is of vital importance for ballasted tracks [24]. Normally, intervals between tamping ranges from 2 to 10 years, depending on type of traffic and degradation rate. Shorter problematic sections may still require tamping several times per year.

Ballast cleaning

The ballast layer can be fouled due to: ballast breakdown, infiltration from ballast surface, sleeper wear, infiltration from underlying granular layers, and subsoil infiltration [55]. This will affect the bearing capacity of the ballast bed and the drainage function, which in turn will give an even worse function of the ballast. According to ERRI, ballast cleaning becomes appropriate when there are more than 30 % of fine graded soil of less than 22.4 mm size in the ballast [24], [21], and is absolutely necessary when there is more than 40 %. A ballast cleaner machine removes the fouled ballast and put cleaned and new ballast back in the track.

Compaction

Compaction is the process of soil densification by mechanical manipulation [55]. The densification is achieved by reduction in volume of the air voids. The reason for compaction is to improve soil properties such as strength, stiffness and permeability. Compaction is most commonly done using surface rollers (static and vibratory). The effect decreases with depth, and is useable to generally 300 – 600 mm. To compact a greater depth with rollers requires removal and replacement of layers.

Admixture stabilisation

Soil properties can be improved by mixing in other materials such as portland cement, lime, bitumen and fly ash [55]. Mixing is best accomplished by special mixing equipment that uses rotating tools to break up the soil and mix it with the additive. Stabilisation of layers close to the surface is often called soil stabilisation, and stabilisation of the subsoil is called deep soil stabilisation. Lots of research has been performed in Sweden coordinated by the Swedish Deep Stabilization Centre, and examples of practical application of lime cement columns can be found in [30], as well as in [60].

Drainage

Too much water content in the substructure can cause series of different problems; therefore drainage is of vital importance [55]. As for most of the substructure issues, drainage should be made properly when building the track. The first requirement to achieve substructure drainage is to keep the ballast clean enough to be able to drain the water as fast as it enters. The second requirement is to have the surface of the subballast and subsoil sloped towards the sides of the track. The third requirement is to provide a means of carrying away the water that comes out of the substructure. Control of ballast fouling followed by ballast cleaning fulfils the first requirement. Reshaping of surfaces to get correct slopes is important for the second requirement. The solution for the third requirement has to be done with consideration of the surrounding water drainage situation. Maintaining a properly built drainage can be easy. Simple actions like flushing culverts can improve the drainage function considerably.

Geosyntethetic applications

The main functions of geotextiles and geotextile-related products used in the construction of railways are filtration, separation and reinforcement [25]. An introduction to railway related use of geotextiles can be found in [55].

Subsoil improvement is often extensive and expensive. There are few techniques that can be used without removing the superstructure; therefore there is a great need for new techniques.

4 VERTICAL TRACK STIFFNESS

Track stiffness (vertical track load divided by track deflection) is a basic parameter of track design which influences the bearing capacity of track, the dynamic behaviour of passing vehicles and, in particular, the quality of track geometry and the life of track components. In general, relatively high track stiffness is beneficial as it provides sufficient track resistance to applied loads and results in decreased track deflection, which reduces track deterioration. However, very high track stiffness leads to increased dynamic forces in the wheel-rail interface as well as on sleepers and ballast, which may cause wear and fatigue of track components. Also, a particular problem is changes in track stiffness along the track, which causes variations in vehicle-track interaction forces and leads to differential settlement and therefore differential track geometry deterioration and potentially vibration problems.

Vertical track stiffness or track modulus has for a long time been regarded as an interesting parameter of the structural condition of the track. Zarembski and Chorus [76] state: "Since the early days of the railroad industry track engineers have desired a reliable method to quantify the response of the track structure to given loads. The ability to specify the load-carrying capacity of tracks, to determine the resulting rail stresses and accompanying track deformation, is considered to be essential to proper track design and maintenance." Winkler and Timoshenko proposed theories to model the track and calculate rail stresses [75], [69]. One of the first attempts to determine static track modulus from experimental data was undertaken by the ASCE-AREA Special Committee on Stresses in Railroad Track in 1918, see [76]. Also in Sweden a test was performed at Säbylundmossen during the 1920s [63]. However, in the 1970s and 1980s there are several references that assess standstill track modulus measurements, mainly with the help of track loading vehicles (TLV) [76], [77], or a rebuilt tamping machine [23]. In Sweden, the first TLV was built in the late 1980s and was used for both static and dynamic measurements [12], [36].

Many research works and literature surveys on track stiffness have been published over the years (See e.g. [9], [11], [28], [34], [45], [70] and references there in). However, understandings about track stiffness and its effect on track performance are far from complete. This is observed by the fact that there is not yet a European standard for vertical track stiffness available, and, more remarkably, in the current version of both TSI HS INF and TSI CR INF track stiffness remains as an 'open point' [14], [20]. This means that track stiffness is known as a basic parameter that refers to the essential requirement 'Technical compatibility'. However, current state-of-the-art knowledge and existing results are not sufficient to derive consensus rules and specifications. Hence, further research and studies are required in order to develop a rational approach to the track design/construction so that the track stiffness and its variations are within an acceptable range of values, or ideally, to achieve an optimum track stiffness. Also, it is important to be able to measure track stiffness using techniques which give accurate, repetitive and reproducible results so that track performance of existing lines can be evaluated and appropriate decisions regarding track maintenance may be made. The latter subject is the core of this thesis.

The following description follows [7] and [9].

4.1 Definitions of track stiffness

Vertical track stiffness (k) can be defined in a number of ways and in its simplest form is the ratio between track load (F) and track deflection (z) as a function of time (t), where the force can be either axle load or wheel load:

$$k(t) = \frac{F(t)}{z(t)} \tag{1}$$

Commonly the stiffness of different components of the track structure, such as the rail pad and subgrade, is nonlinear. Further, the sleepers may also have voids beneath them, which lead to large deflections with low loads as indicated in Figure 2. To take into account these factors other definitions of track stiffness may be used. For example, to eliminate the effect of voiding the secant stiffness may be used as follows: (in Eurobalt II calculated between 10 and 70 kN (axle load of 20 – 140 kN)) [45].

$$k_{x-ykN} = \frac{F_y - F_x}{z_y - z_x} \tag{2}$$

Where F_x and z_x are the seating load and resulting deflection respectively.

Alternatively the tangent stiffness can also be used:

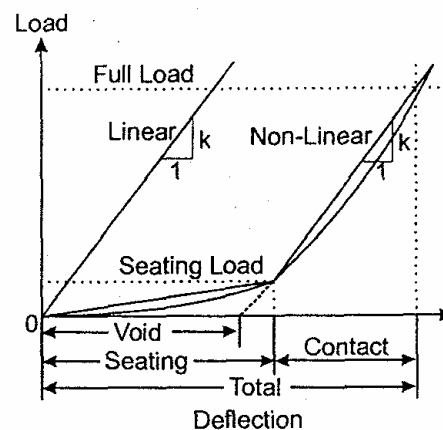$$k_{tng,y} = \left| \frac{dF(t)}{dz(t)} \right|_y \tag{3}$$

Figure 2. Load – deflection diagram illustrating voids and non-linearities (after Sussmann et al. [66]).

Examples of measured vertical track stiffness are shown in Figure 3. Figure 3a displays a force-deflection diagram where the rail is slowly (quasi-statically) loaded up to 150 kN while the corresponding deflection is measured. The curve is non-linear and also has a hysteresis, which indicates a damping factor.

To facilitate the analysis of dynamic track stiffness using Fourier transforms and associated transfer functions, it is necessary to assume that the stiffness is linear about a certain reference

preload. This presumption is approximately valid for a limited portion of the force-deflection diagram. The transfer function between force and displacement is called receptance (α) or dynamic flexibility, Eq. 4. The receptance is a complex-valued quantity and is often displayed with magnitude and phase. Receptance is the inverse of the dynamic stiffness and is used in preference to it as most systems studied are force driven and so resonance phenomena can be interpreted as large deflections [26].

$$\alpha(f) = \frac{z(f)}{F(f)} \qquad (4)$$

An example of receptance magnitude, where the same track as in Figure 3a is loaded statically by 90 kN and dynamically by 10 kN, is shown in Figure 3b. In this particular case we find a resonance around 5 - 8 Hz due to soft soil (clay). We also see that the track is stiffer (lower receptance) for higher frequencies, at least up to 50 Hz.
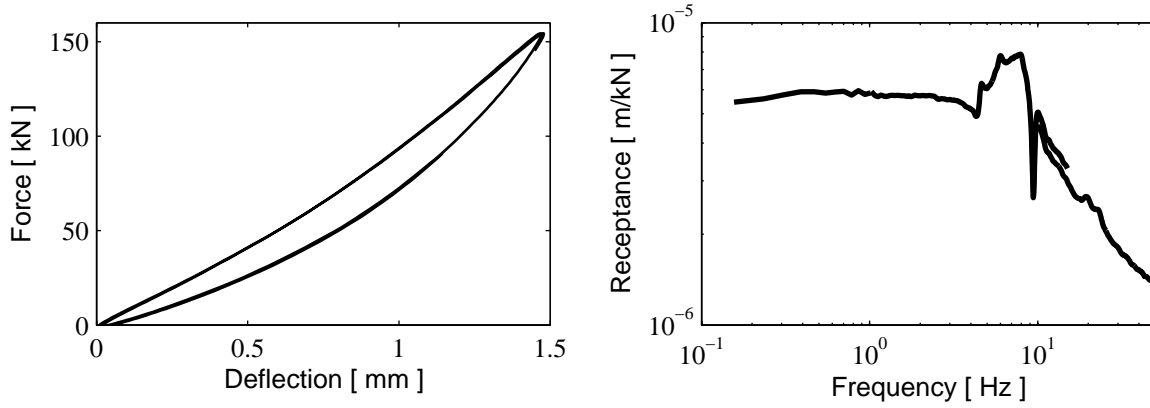

Figure 3. a: Vertical force-deflection diagram of track with quasi-static excitation (measured on rail), **b**: Magnitude of vertical track receptance with subsoil of clay (measured on rail), $F_{stat} = 90$ kN, $F_{dyn} = 10$ kN. Measurements made by Banverket with standstill track-loading test vehicle at Svealand line km 37+537 [Paper A].

The track modulus, u, is defined as the applied force per unit length of rail per unit deflection (δ) (unit Pa), Eq. (5), and is sometimes used instead of track stiffness:

$$u = \frac{q}{\delta} \qquad (5)$$

where q is the vertical foundation supporting force per unit length. Using the theory of a beam on elastic foundation, a relationship between track modulus and track stiffness can be found as follows [54]:

$$u = \frac{k^{4/3}}{(64EI)^{1/3}} \qquad (6)$$

The difference between u and k is that k includes the rail bending stiffness EI, whereas u is related only to the remainder of the superstructure (i.e. fasteners and sleepers) and the substructure (ballast, subballast and subsoil).

Selig and Li [54] suggest that a track modulus of $u = 28$ MPa may be considered a minimum to ensure a consistently good track performance under traffic loading. This equals (Eq. (6)) to a stiffness of $k = 55$ kN/mm (one rail) with the rail type UIC 60. Based on studies of the Spanish high-speed line between Madrid and Seville, Lopez Pita et al. [42] propose that an optimal stiffness value for high speed tracks is about 70 – 80 kN/mm (one rail) on a maintenance costs and energy consumption (running resistance) basis.

4.2 The role of track stiffness measurements in track maintenance

Several references point out vertical track stiffness as important for track maintenance. Esveld states [24]: "Track stiffness has been found to be very useful for the purpose of determining the cause of certain substructure problems. Unfortunately, in most of the cases railways do not possess the right equipment for this type of measurement and, thus, do not utilize the insight these measurements could have provided them with". Sussmann et al. state [66]: "Track stiffness test provides a potentially useful technique for systemwide evaluation of track safety and performance. The data can be used to provide an additional indicator of track condition to inspectors and to guide maintenance planning and execution." Fröhling states [28]: "Spatial variation of the track stiffness contributes significantly to track deterioration, both in terms of differential track settlement and increased dynamic vehicle loading. It is thus recommended that track maintenance procedures should be used to reduce the variation of the spatial track stiffness." Ebersöhn and Selig state [15]: "The continuous measurement of track deflection or stiffness and the correct interpretation of the results will be a tool for the track maintenance engineer to correctly direct the maintenance activities which will result in optimal use of the maintenance budget."

The stiffness that the trains will experience is the total track stiffness, including everything from the rail Young's modulus of elasticity (E) and the rail moment of inertia (I) through the resilient pad to the sleeper, ballast, subballast and subsoil. There are several different ways of modelling railway tracks that have been developed since the early days of Winkler [75]. Some of the research work performed in Sweden can be found in [46] and [48]. In Figure 4 one of the simplest models of the system is shown.
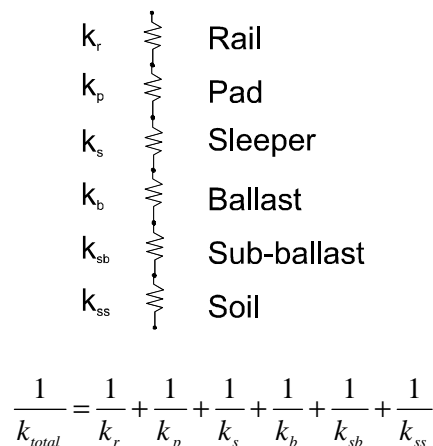

$$\frac{1}{k_{total}} = \frac{1}{k_r} + \frac{1}{k_p} + \frac{1}{k_s} + \frac{1}{k_b} + \frac{1}{k_{sb}} + \frac{1}{k_{ss}}$$

Figure 4. Simplified model of the total track stiffness.

Most of the components can be highly nonlinear in behaviour and vary with for example temperature, moisture content and applied preload. The stiffness of all these components can also vary along the track. This will of course make it more difficult to resolve what part of the structure that is responsible for what discrepancy. Selig and Li [54] performed a parametric study with the software GEOTRACK, to find out the potential effects different track components have on track modulus.

This study clearly showed that the subgrade (soil) properties had most impact on the total track modulus. The authors summarize the parametric study: "The factor affecting the track modulus most is the character of the subgrade layers. The influence of subgrade condition on track modulus is further enhanced by the fact that the subgrade resilient modulus is the most variable quantity among all the track parameters, subject to change of soil type, environmental conditions, and stress state. Therefore, a change of track modulus in the field is primarily an indication of a change of subgrade condition. Since the subgrade condition is subject to weather, extremes of temperature and moisture, the track modulus may vary with seasonal changes."

There are several different areas where track stiffness measurements have potential for supporting track maintenance decisions: indicator of root cause at problem sites, upgrading of track for higher speed and/or axle load, verification of newly built track.

Indicator of root cause at problem sites

Measurement of track geometry quality is the most used automated condition assessment technique in railway maintenance. Most problems with the track (at least the ones concerning the ballast and substructure) will be visible as track geometry irregularities, but the root cause of the problem is not detected with the help of track geometry measurements. In these cases, track stiffness measurements can help finding the root cause of the problem [15], [52], [54], [56], [66]. However, it is also important to be aware of that track stiffness measurements can not indicate the root cause problem in all cases.

The main causes of subsoil problems are described by Li and Selig [40] as:
- **Load factor:** There are two types of load factors, material dead-weights and repeated dynamic loading.
- **Soil factor:** A problem subsoil will not generally consist of coarse-grained soils (gravel and sand) but most likely will be fine-grained soils (silt and clay) because of the lower strength and permeability of the latter materials.
- **Soil moisture:** Almost every subsoil problem can be attributed to high moisture content in the fine-grained soil. The presence of water in the subsoil can reduce the strength and stiffness of soils dramatically.
- **Soil temperature:** Soil temperature is of concern when it causes cycles of freezing and thawing.

Most often a subsoil problem area will involve several of the above mentioned factors. Track stiffness is influenced by all factors, though it is not always possible to distinguish them or determine the most influencing factor. The methodology described in Paper G, might be a possible way for classification among these causes.

Sussmann et al. [66] try to relate different kind of track problems with track stiffness and maintenance action. Table 1 summarizes their findings:

Table 1. Relation between stiffness and track problem / maintenance [66].

Parameter	Problem	Maintenance / Rehabilitation
Low track stiffness	Poor or weak subsoil or fouled ballast	Substructure design, Stabilize subsoil
Variable track stiffness	Variable track support (stiffness or modulus)	Matching rail seat pads, Substructure design, Ballast mats
Void sleepers	Fouled ballast, Local settlement, Poor fastener condition	Inspect fasteners, Tamping, Stoneblow, Undercut

They suggest that the cause of unacceptably low values of track stiffness are mostly likely to be an indication of a weak subgrade as the properties of the subgrade most influence the value of track stiffness. In some cases the weakness may be attributed to poor drainage. However, by the time the problem has fully manifested itself the redesign and reconstruction of the track substructure may be required to reduce the traffic induced stresses in the subgrade to acceptable levels. Alternatively, methods of soil reinforcement to increase the strength and stiffness of the subgrade can be used.

In some cases low track stiffness values can also result from fouled or dirty ballast that prevents adequate support for track loading. This problem occurs especially when the ballast and subgrade deteriorate in the presence of water due to train induced repeated loading. The resulting migration of fines into the ballast and subsequent formation of wet spots, can lead to a reduction in stiffness of the track support system and hence loss of track geometry. Whilst replacing, or cleaning, the ballast may improve the problem in the short term, longer term solutions may require; the improvement of the drainage; the use of appropriate materials at the subgrade/ballast interface to reduce pumping and the migration of fines, and; in particularly problematic cases redesign and reconstruction.

For the problem of an unacceptable variability in track stiffness Sussmann et al. [66] suggest that potential solutions include the design of rail seat pad stiffness, the appropriate design of the substructure and the use of under ballast mats.

Sometimes large deflections may occur under load indicating the presence of hanging sleepers or loose rail seat fasteners. These types of problems can usually be fixed by repairing fasteners, the appropriate tamping or stone blowing of the ballast, and undercutting when the void is due to fouled ballast that deforms easily under a load [66].

An additional consideration, although one which occurs less often, are problems associated with high stiffness which can lead to faster deterioration of the track and its components due to higher dynamic loads. In such cases several methods may be used to reduce the stiffness including the installation of soft pads and resiliently mounted sleepers [29], [53]. Soft pads, however, may have an undesired side effect of increased noise radiation.

The noise radiated by the track is a function of, amongst other things, the receptance of the rail and particularly the stiffness of the rail pad between the rail and the sleeper [38]. For noise, only frequencies in the audible band are of interest (i.e. 20 – 20000 Hz). The upper limit as seen from the track is 2000 – 5000 Hz [29]. There is, obviously noise at higher frequencies, for example wheel and braking noise, but the track (rail) is not the dominant source. Whilst soft pads may reduce track stiffness effectively they can increase noise

emanating from the rail as their use causes the rail effectively to become uncoupled from the sleeper. This minimizes noise from the sleeper but enables the rail to vibrate more freely so that waves can travel over a greater distance, increasing the noise from the rail. Conversely, with stiff pads the contribution from the rail is reduced but that from the sleepers is increased [38].

Ground borne vibration problems are associated with subgrade soils of low stiffness and/or a clear resonance as these tend to propagate vibrations more effectively. Smekal et al. [61] give an example of how such potentially problematic sites may be identified. The measured track stiffness though, is the total stiffness and does not only consist of the soil stiffness. A vibrating clay soil with a high embankment can have the same medium stiffness as a normal vibrating gravel soil with a low embankment. Paper C shows how soft soil properties can be estimated from dynamic stiffness measurements. Stiffness phase can often reveal soft soils that may be vibration susceptible. This is clearly visible in the stiffness statistics reported in Paper G.

Upgrading of track for higher speed and axle load

The trend towards using faster trains and heavier axle loads than those originally considered in many cases compel upgrading of existing tracks. There are many aspects that have to be considered when upgrading a track, and among them are bearing capacity, stability, and future maintenance need of the track. Infrastructures like for example bridges are in some sense known structures in terms of materials and can be subjected to visual inspection. The substructure of the track is on the contrary often unknown and only limited visual inspection is possible. The possibility to measure the vertical track stiffness could be a help for determining which sites along the track that need some kind of substructure reinforcement or further investigation.

Verification of newly built track

During design of a new track, track stiffness is most often considered with questions like: What is the desired rail deflection? How long transition zones at bridges etc. shall be used? Different design aspects can be found in [9]. In the study by Lopez Pita et al. [43], changes of track stiffness through culverts and bridges were considered the main causes of track deterioration. There is a lack of recommendations for track stiffness variability; however the Eurobalt II project recommended that variations in the stiffness of the subgrade should be limited to less than 10% of the mean value [45]. With the help of continuous track stiffness measurements, it is possible to verify newly built tracks; both for stiffness magnitude and variability.

4.3 Vertical track stiffness measurement techniques

There are a number of methods which may be used to measure the vertical track stiffness. Perhaps the most important distinction is between those that make measurements at discrete intervals whilst standstill, and those that measure stiffness continuously whilst moving (i.e. rolling measurement). Standstill measurements have been more widely used, often for research purposes, whereas rolling measurement techniques are in their infancy nevertheless more useful for production measurements.

As mentioned previously, track stiffness is a function of frequency and it is necessary to select an appropriate device for measurement depending on the frequency of interest. The static and low frequency dynamics of the track are mostly related to geotechnical and geodynamical issues. Measurements of track stiffness at these frequencies may be very useful for investigations related to the bearing capacity of the subgrade, ground borne vibrations and some soft-soil related problems. High frequencies relate to problems associated with noise and train-track interaction forces.

4.3.1 Standstill measurements

Amongst the number of standstill devices available for measuring track stiffness, four are described. These are by the use of simple instrumentation, the impact hammer, the FWD and track loading vehicles.

A very simple method of measuring track stiffness can be achieved by instrumenting any number of sleepers, and/or rails, with displacement transducers or accelerometers and measuring the response during the passage of a train. The associated stiffness can then be calculated for that track section if the axle load is known. For improved accuracy, where dynamic loads are taken into consideration, the load from the train can also be measured with the help of strain gauges on the rail web, or on the sleeper. The typical results from such a measurement are load – deflection diagrams, where the stiffness can be identified with any of the above definitions of stiffness.

The impact hammer is a handheld device which is used to hit the rail or sleeper [50]. The hammer head is equipped with a force transducer to measure the impulse, and an accelerometer is attached to the rail head or the sleeper. The transfer function between the impulse force of the hammer and acceleration of the rail is calculated (often it is also double integrated to get receptance instead of accelerance). Typically, a frequency interval of 50 – 1500 Hz can be covered using the hammer depending on the material used for the top of the hammer head. Rubber gives lower frequencies than a metal top for example. Since frequencies below 50 Hz are not recorded, impact hammer tests are most suited to problems associated with noise, vibration and wheel-rail contact forces.

The Falling Weight Deflectometer (FWD) is a device which is most often used to measure the stiffness of the track structure excluding the rails [8]. The standard FWD device consists of a mass that is dropped from a known height onto rubber buffers mounted on a footplate. The resulting impact is measured by a load cell on the centre of the plate and velocity transducers are used to determine surface velocity at various distances, *d* from the footplate. The velocities are integrated to give vertical displacements. For railway tracks in the UK, the device is designed to apply a 125 kN load to a sleeper, disconnected from the rails, via a 1.1

m long loading beam shaped to distribute the load to both ends of the sleeper. This loading system is considered to produce a load pulse which is similar to that applied by a single axle of a train travelling at high speed [58]. The magnitude of the applied load is measured in the centre of the loading beam and the velocity transducers are positioned on the loaded sleeper and on the ballast at various distances from the centre of the beam.

The track stiffness is calculated from the load and deflections measured at some of the geophones, depending on the application. For example, if the stiffness of the ballast and sub-ballast layers is to be established the track stiffness is often determined from the load and deflections measured immediately under the load (d_0) and from those measured by geophones 1000 mm from the load (d_{1000}) as follows [9]:

$$k = \frac{62.5}{(d_0 - d_{1000})} \text{ kN/mm/sleeper end} \qquad (7)$$

A Track Loading Vehicle (TLV) uses its own weight to load the track with the help of hydraulic jacks. Usually the rail heads are loaded, but the sleeper can be loaded also with the rails decoupled. Depending on the equipment different loads can be applied.

There are not so many TLV:s worldwide; examples include those developed in the USA by the Transportation Technology Center, Inc. (TTCI) [68], [16] and the DECAROTOR [10]; the South African BSSM [16], and a modified tamper described by Esveld [23]. The Swedish TLV which has a weight of 49 tons, can load each rail statically up to 150 kN and excite dynamically up to 200 Hz (see Figure 5). It can also measure lateral track stability/stiffness [39]. The main advantage of a standstill TLV compared to rolling measurements is that the preload, dynamic load and frequency range can be varied to a greater degree. However, the process is much more time consuming and requires the railway track to be closed.
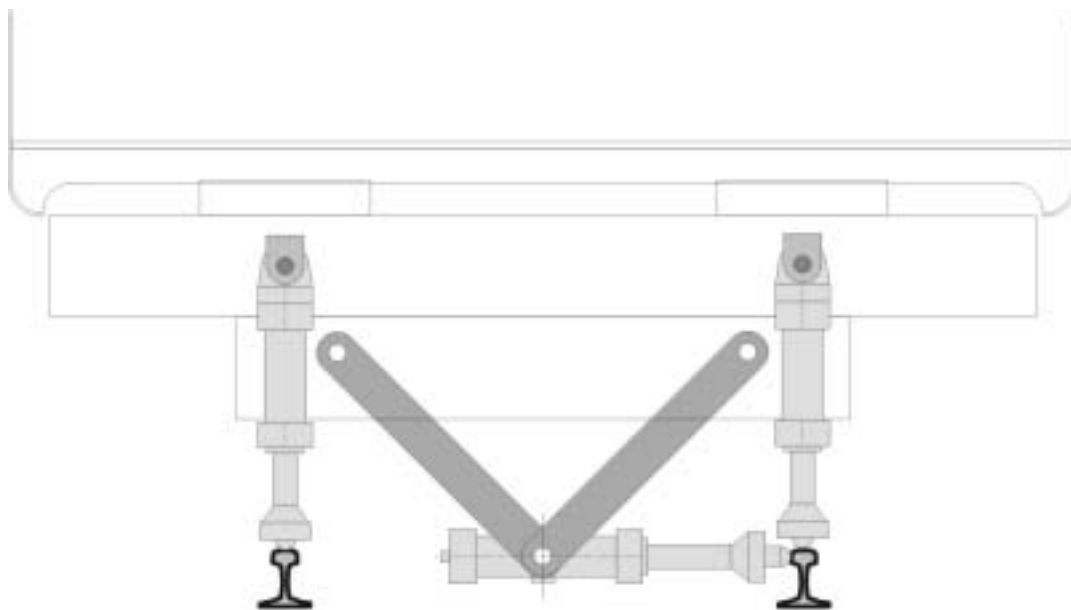

Figure 5. The vertical and lateral hydraulic actuators of the Swedish TLV.

4.3.2 Rolling measurements

If standstill measurements have been used mainly for research purposes, rolling measurements have the potential to be used on a more regular basis for maintenance purposes. Whilst there are several different systems for measuring the vertical track stiffness along the track, most measure the displacement under one or two axles caused by the weight on the axles and the track flexibility. With knowledge of the static axle loads, the track stiffness can be calculated. In case of a two-axle system, the axle loads are different and the lightest loaded axle is used to remove the effect of track irregularities on the stiffness measurement. There are also devices based on dynamic measurements on a single axel. The development of such a device is described thoroughly in Paper A and B.

The vertical track stiffness measured by each device is unlikely to be identical for a number of reasons as follows:

- **Static preload:** The static preloads applied are different and are therefore likely to result in different stiffness values being recorded for the same section of track.
- **Excitation frequency / speed:** Equipment using a static running wheelset to load the track will excite the track with a range of frequencies which is a function of the speed of the vehicle. As the measuring speed increases, so will the frequency content. Since the dynamic track stiffness is not constant with frequency, the stiffness determined is likely to differ.
- **Spatial resolution:** The different measurement techniques may have different spatial resolutions.
- **Model dependency:** The devices measure the deflection of the rail different distances away from the wheelset. Where the deflection is not measured directly under the wheelset a model for the rail bending has to be used in order to calculate the rail deflection under the wheelset. These models are approximations of reality and can introduce uncertainty and related errors.
- **Degree of influence from track irregularities:** Track geometry irregularities, especially those associated with the longitudinal level can influence the stiffness measurements since the displacement transducers used in the equipment in most cases measure a combination of deflection due to track flexibility and displacement due to track geometry irregularities. Wheel out-of-roundness and wheel flats introduce similar disturbances.

A number of organisations have developed rolling devices to measure track stiffness. Some of these are summarised below:

CARS, People's Republic of China [73]

The China Academy of Railway Sciences (CARS) was one of the first organisations to develop a system for continuous track stiffness measurement [73]. Their system, which travels at speeds of up to 60 km/h, uses two track geometry chord measurement systems with different loading applied to each of the measurement axles (Figure 6). The light-weight car has a weight of 40 kN and is used to reduce the effect of track geometry irregularities on the stiffness measurement recorded by the heavy-weighted car. A weight of 40 kN was chosen as it was found to be sufficient to reduce the effects of voided sleepers. The axle load of the heavy-weighted car can be varied between 80 and 250 kN enabling the nonlinear characteristics of the same section of track to be investigated by repeating with different loads. From personal communications with Mr Wangqing [74], track stiffness of 65 – 100 kN/mm (one rail) is desirable.
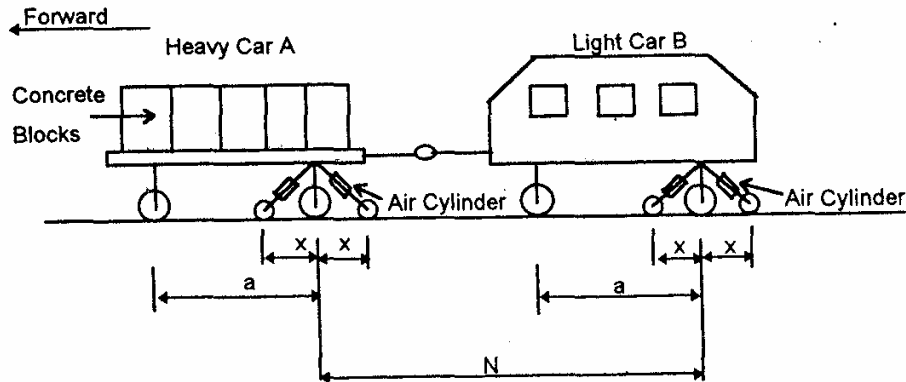
Figure 6. Principle of Chinese track stiffness measurements [73].

TTCI, USA [68], [41]

TTCI's track loading vehicle (TLV) has been developed to measure both lateral and vertical stiffness at standstill and when moving at speeds of up to 16 km/h [41], [68] For rolling vertical stiffness measurements the TLV for standstill measurements is coupled with an empty tank car.

The TLV has a fifth wheelset (loaded bogie) mounted underneath the vehicle centre, that can be loaded hydraulically (both vertically and laterally) with vertical loads between 4 – 267 kN. A load of 178 kN is applied to the test axle of the static TLV. If two separate runs are used to differentiate the supports between the ballast and the subsoil, a light test axle load of 44 kN is used for the second run. The deflection is measured with the help of laser sensors, yielding a chord measurement of rail bending deflection (see Figure 7).
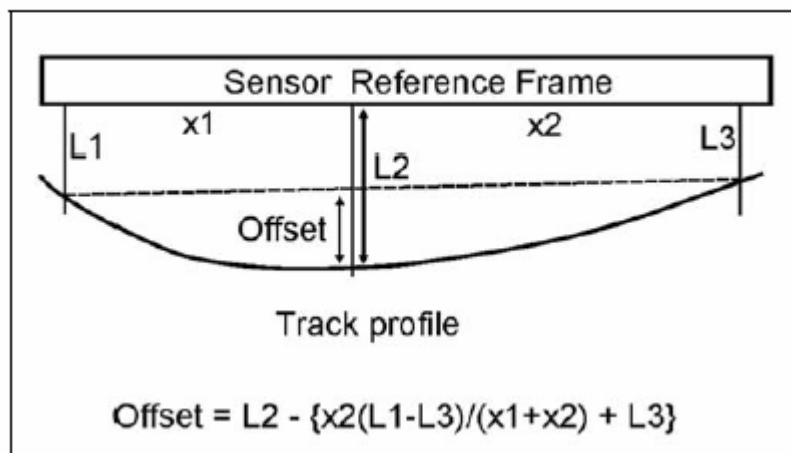

Figure 7. Rail bending deflection measurement with lasers, yielding chord values [41].

Measurements are also made under the empty car, which is also equipped with a centre loaded bogie with pneumatic actuators capable of applying a nominal load of 9 kN.

18

The low load measured deflection represents track irregularities, and by taking the difference between the high and low load measured deflections, only the flexibility of the track remains.

Banverket, Sweden [Paper A, B]

The measurement technique of the Swedish method is the main theme of Paper A and B. Case studies and methodology for interpretation can be found in Paper C, D, and G.

A prototype trolley was developed during the Eurobalt II project 1998 - 2000 which could be used for rolling stiffness measurements together with the Swedish TLV. The Eurobalt II project (EUropean Research for an Optimised BALlasted Track) was a joint research project with several rail administrations, rail industries and universities from France, Germany, UK and Sweden. The project was supported by the European Commission's Brite-Euram III programme project nr. BE96 – 3263. The measurement device is described in Paper A.

After successful measurements indicating large potential, a new vehicle was built during 2003 – 2004. The new vehicle, called RSMV (Rolling Stiffness Measurement Vehicle), is a rebuilt two-axle freight wagon. The track is dynamically excited through two oscillating masses above one of the ordinary wheel axles as shown in Figure 8 and Figure 9. Track stiffness is calculated out of measured force and acceleration as described thoroughly in Paper B.

Figure 8. The measurement equipment in the RSMV (vertically moving masses above measuring axle, contained in steel cages).

The static axle load is 180 kN and the maximum dynamic axle load amplitude is 60 kN. The RSMV can measure the dynamic track stiffness up to 50 Hz. Both overall measurements at

higher speeds (up to 50 km/h) with 1 – 3 simultaneous sinusoidal excitation frequencies or detailed investigations at lower speeds (below 10 km/h) with noise excitation can be performed.
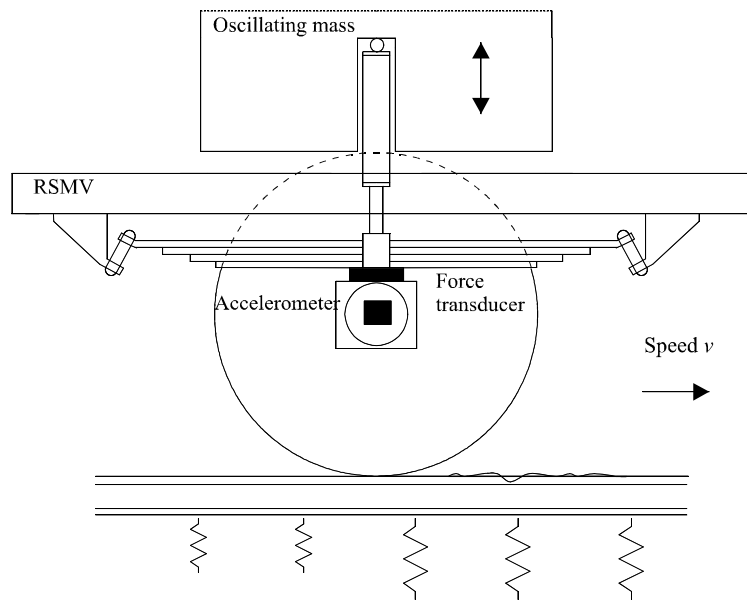

Figure 9. Measurement principle (one side only) of RSMV.

University of Nebraska, USA [44], [47], [27]

The University of Nebraska at Lincoln (UNL) in the USA has developed a system to measure track stiffness [3], [47]. The technique uses line-lasers to measure relative rail deflection between the bogie and the rail [44].

The measurement principle is shown in Figure 10 and Figure 11. The relative deflection is measured using two lasers and a camera that measures the distance, *d*, between the two lines and as the sensor moves with respect to the rail surface, the distance between the laser lines changes. The Winkler model is used to relate the measured deflections to track modulus/stiffness.
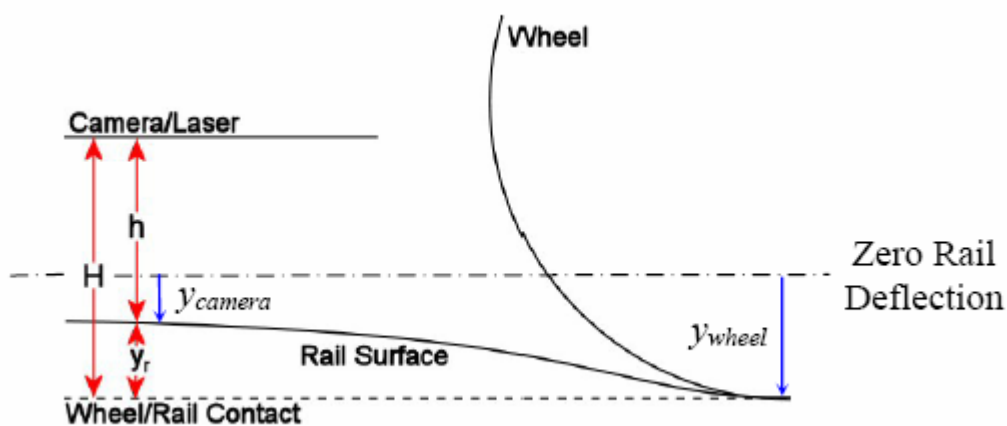

Figure 10. Rail deflection / Sensor measurement of UNL-stiffness equipment [47].
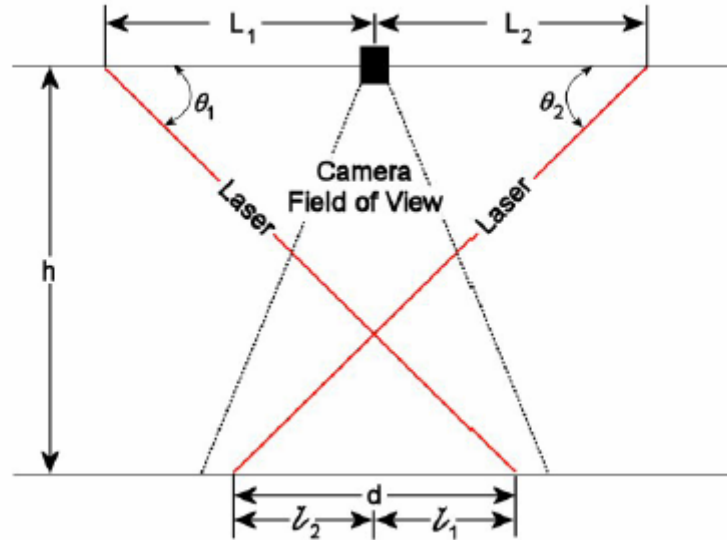
Figure 11. Sensor geometry of UNL-stiffness equipment [47].

CETE, France

The French Portancemeter is a stiffness monitoring tool designed by CETE-Normandie Centre for road structures and is currently being adapted for use on railways [31], [32]. The device applies a dynamic load to the track via a vibrating wheel suspended by a spring and a damper. For road testing 10 kN of static weight, 0.5 mm of theoretical amplitude at 35 Hz is used. For rail testing these characteristics will be changed with increased loads (both static and dynamic) and the capability to alter the frequency. In the current (2006 – 2009) European research project Innotrack, a comparison measurement will be performed between the portancemetre and the RSMV.

SBB Switzerland

Swiss Railways, Schweizerische Bundesbahnen (SBB), has developed a device (see Figure 27) which is similar to the Chinese and TTCI equipment and uses two geometry measurement systems [62].

Figure 12. Swiss track stiffness measurement vehicle [62]

FRA / Ensco / Volpe Center [67]

Recently a test has been performed by Ensco and Volpe National Transportation System Center, sponsored by FRA [67]. The idea is to instrument two axles, with different static load, with accelerometers. After double-integrating the accelerations the result are two track geometries (longitudinal level) from different loads. From this result, the system is in principle similar to that of China, TTCI, and SBB. The measurement system is made rather uncomplicated and as sensor technology develops, accuracy may be sufficient.

Other published methods

A rebuilt tamper has been used in Czech Republic for track stiffness trials [71], [72].

TU Delft had a promising project around year 2000, but didn't build a prototype for railway measurements [49], [50], [51], [24]. The High Speed Deflectograph (HSD) makes use of laser doppler sensors attached to a moving railway vehicle, travelling at speeds of up to 130 km/h, to measure the rail bending velocity. The HSD has a number of advantages over other rolling devices including:
a) the effect of track geometry irregularities on the measurement of track stiffness is much less than when displacement transducers are used, although the effect of hanging sleepers still contributes to the rail bending velocity;
b) the rail bending velocity increases with train speed and as a result higher trains speeds are likely to produce more accurate results.

Non-published methods

In the Eurobalt II project, SNCF in France examined a method to measure stiffness, by using an unbalanced wheel on a TGV test train [37]. This is also a dynamic excitation of the track (approximately 28 Hz with a travelling speed of 300 km/h).

The company ZG Optique in Switzerland offers rolling stiffness measurements at their homepage [78]. They will try to apply for a patent on the method and therefore it is not published at present.

A comparison between the different methods is hard to perform without measuring the same track. The accuracy and applicability of the methods is of course important and not all of the above mentioned methods have shown confident results. The travelling speed is also very important having in mind large occupancy of the tracks and large networks to measure. Since track stiffness is a complex area, the possibility to measure more than one aspect (for example frequency and preload) is an advantage. Another important factor to have in mind when comparing different methods is resolution with distance; stiffness could vary fast and we are not interested in mean values over longer distances.

Lateral Track Stiffness Measurement

Lateral track stiffness is associated with track stability (resistance against track buckling) and whilst it has not been discussed in this chapter in any detail, it is an important parameter. Both the Swedish TLV and TTCI's TLV are capable of its measurement.

5 PRESENT WORK

In addition to this introductory part, the thesis comprises eight papers, Paper A – H. They are all summarized in this chapter.

5.1 Summary of Paper A

Paper A, *Continuous Track Stiffness Measurement, An Effective Method to Investigate the Structural Conditions of the Track,* describes the prototype trolley developed for dynamic vertical track stiffness measurements during the Eurobalt II project. The measurement technique is described as well as the evaluation technique for sinusoidal excitation. Several tests with different excitation frequency and speed combinations are reported as well as repeatability/reproducibility investigations. A significant correlation between track stiffness and the geotechnical conditions was found. The prototype trolley has some limitations; it can not measure in turnouts or in curved track with radii less than 1200 m. The maximum measurement speed is 30 km/h. The paper was presented by Eric Berggren at the Railway Engineering Conference in London 2002.

5.2 Summary of Paper B

Paper B, *Simulation, Development and Field Testing of a Track Stiffness Measurement Vehicle*, describes the new track loading vehicle of Banverket, called RSMV (Rolling Stiffness Measurement Vehicle). It is a development from the prototype trolley described in paper A, but the new vehicle has not the limitations of the trolley. Also the load and speed capabilities are better. Before the development of the RSMV, simulations with the rail vehicle dynamics software GENSYS were performed to ensure the measurement and evaluation principles as well as the vehicle running behaviour. The RSMV is a rebuilt two-axle freight wagon with two oscillating masses above one of the wheelsets capable of exciting the track dynamically while rolling. The measurement technique is described as well as the evaluation method for sinusoidal and noise excitations. With sinusoidal excitation the measurement speed can be up to 50 km/h and with noise excitation the measurement speed should be below 10 km/h. Repeatability tests, comparison with the old prototype trolley and measurements on soft soils are also reported in the paper. The paper was presented by Eric Berggren at the 8th International Heavy Haul Conference in Rio de Janeiro in 2005. The paper was awarded with a Best Paper Award at the conference.

5.3   Summary of Paper C

Paper C, *Identification of Substructure Properties of Railway Tracks by Dynamic Stiffness Measurements and Simulations*, focuses on the low-frequency dynamic behaviour of tracks with soft soils. With the help of simulations in the software *VibTrain*, the dynamic behaviour of soft soils is categorized. Parametric studies have been performed for the substructure properties shear wave velocity, depth of soil layer and how deep in the track structure the soft soil is situated (equivalent embankment). Out of the simulations, some features – as for example minimum phase delay and corresponding frequency of the receptance function – that describe the dynamic behaviour are extracted. These features are analysed with techniques from the field of pattern recognition to extract the substructure properties. Two case studies with measurements from the RSMV and geotechnical investigations are used to exemplify the methodology. The paper concludes that it is possible to estimate (equivalent) thickness of embankment and to give reasonable estimates on shear wave velocity and thickness of clay layer. The paper is resubmitted for publication.

5.4   Summary of Paper D

A case study is reported in Paper D, *Monitoring and Substructure Condition Assessment of Existing Railway Lines for Upgrading to Higher Axle Loads and Speeds*. For a track considered for increased axle load from 22.5 to 25 metric tonnes, several measurements were conducted. Besides the standard track geometry quality measurements, also dynamic track stiffness and GPR were measured. All measurements were imported to the software RDMS (Railway Data Management System) where a synthesized analysis was performed. Suggestions on upgrading activities were given in the study. The paper was presented by Alexander Smekal at the World Congress of Railway Research in Montreal 2006.

5.5   Summary of Paper E

Special attention to short-waved irregularities is given in Paper E, *Measurements of Track Stiffness and Track Irregularities to Detect Short Waved Support Conditions*. In order to study the excitation mechanism of environmental vibrations, both short-waved stiffness and geometry (longitudinal level) irregularities were studied. Stiffness measurements in low speed were performed to ensure high spatial resolution. Variations of 5 – 20 kN/mm (2 – 10 %) between adjacent sleepers are common, and variations up to 60 kN/mm (30%) have been detected on a modern ballasted track. (Figures relates to axle load (both rails).)

Also a new way of analysing longitudinal level by filtering out only short-waved irregularities is proposed. This makes it possible to indicate problems with hanging sleepers, variable sleeper support and other possible short-waved irregularities. The amplitude of these irregularities is low (around 0.5 – 1 mm), however, their impact can be considerable. The paper was presented by Eric Berggren at the conference Railway Track Foundations in Birmingham 2006.

5.6   Summary of Paper F

Paper F, *A New Approach to the Analysis and Presentation of Vertical Track Geometry Quality and Rail Roughness*, also investigates geometry irregularities. Rail irregularities, denoted rail roughness or corrugation, is evaluated in a new way making it possible to easily grasp problem location and wavelength content. The essence of the evaluation is to transform the magnitude of irregularities by a standard spectrum, amplifying the shortest waves. Track irregularities are revealed to have similar wavelength characteristics and can be handled in similar ways. However, as train-track interaction forces are significant, an efficient linear calculation model is developed. The model is based on simplified train-track interaction and by means of system identification transferred into a linear filter. The paper was presented by Eric Berggren at the Contact Mechanics conference Brisbane 2006. It is also published in the Journal of Wear.

5.7   Summary of Paper G

In paper G, *Efficient Track Maintenance - Methodology for Combined Analysis of Condition Data,* a methodology to automate evaluation of condition data is proposed. By means of statistical methods condition data can be classified to different classes depending on the question at hand. The methodology is demonstrated on a large set of condition data originating from track geometry quality, dynamic track stiffness and ground penetrating radar. The case study gives evidence for the importance of dynamic stiffness measurements as to determine soil and embankment related track problems, while problems originating from the upper part or the track structure do not benefit significantly. The paper will be presented by Eric Berggren at the International Heavy Haul Conference in Shanghai 2009.

5.8   Summary of Paper H

Paper H, *A Study of the Effect of Global Track Stiffness and its Variations on Track Performance: Simulation and Measurement*, examine track stiffness from a track engineering perspective. Based on simulation of train-track interaction the stiffness influence on e.g. rail bending moment and interaction forces is investigated. Optimal track stiffness is a trade-off between the values of several parameters, and none of them should be allowed too large. A compilation of stiffness measurements in Sweden is also presented. Stiffness variations are quantified and certain differences appear. The superstructure (i.e. rail weight pad and sleeper type) has unambiguous influence on global track stiffness magnitude. Swedish soft soils (clay/peat) are often distinguished both by track stiffness magnitude and phase. The paper will be presented by Martin Li at the International Heavy Haul Conference in Shanghai 2009.

6 CONCLUSIONS AND FURTHER WORK

The international literature has identified vertical track stiffness as an important parameter for track maintenance and track maintenance management. Track stiffness is a complex area though and understandings about track stiffness and its effect on track performance are far from complete. This is observed by the fact that there is not yet a European standard for vertical track stiffness available. Depending on what frequency considered, quite different fields of railway engineering come in question. The static and low frequency dynamics of the track is mostly related to geotechnical and geodynamical issues. Such track stiffness measurements might be very useful for investigations related to for example bearing capacity, ground borne vibrations and some soft-soil related problems. High frequencies relate to problems like noise and train-track impact forces. This thesis describes dynamic stiffness measurements at lower frequencies and suggests usage of the same in track maintenance.

A new vehicle, called RSMV (Rolling Stiffness Measurement Vehicle), has been developed. This vehicle is capable of exciting the track dynamically at frequencies between 3 and 50 Hz at speeds up to 50 km/h. Also various studies are presented on how to use track stiffness and related condition data. A methodology for how to automate the evaluation phase through pattern classification is presented as well.

In the introductory part of the thesis, the role of track stiffness in track maintenance is explained. Few railroad organisations have access to measurement devices; therefore not so many practical investigations are at hand. The appended papers elucidate dynamic track stiffness measurement and evaluation of the same in detail. Dynamic track stiffness measurements reveal important information about the track substructure and can be a support for maintenance and renewal decisions of railway tracks.

The area of track stiffness is broad, both from a modelling and a measurement point of view. Future research should continue to study the relation between track substructure deterioration (settlements and track irregularities) and track stiffness. Consensus of track stiffness as a design and maintenance parameter is desired, preferably in an international standard describing optimal span of stiffness and recommended variations. Adopting pattern classification, as is a fact in other disciplines (e.g. search tools on the internet etc.), as described in Paper G might change railway maintenance management in a 10 – 15 year horizon.

From a measurement point of view, a continuous measurement device for track stiffness at higher frequencies would be a challenge. As substructure maintenance often is extensive and expensive, there are also needs for new methods to improve the substructure.

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