Dynamic Vehicle-Track Interaction of European Standard Freight Wagons with Link Suspension

by

Per-Anders Jönsson

Doctoral Thesis

TRITA AVE 2007:36
ISSN 1651-7660
Academic thesis, which with the approval of the Royal Institute of Technology (KTH), will be presented for public review in fulfilment of the requirements for a Degree of Doctor of Philosophy.

Royal Institute of Technology
School of Engineering Sciences
Department of Aeronautical and Vehicle Engineering
Division of Rail Vehicles
SE-100 44 Stockholm
Sweden
Phone +46 8 790 6000
www.kth.se
Contents

Preface and acknowledgements ................................................iii
Abstract ........................................................................... v
Outline of Thesis ............................................................... vii
Contribution of Thesis ......................................................... ix
1 Introduction .................................................................. 1
2 European Freight Wagon Running Gear ............................... 3
   2.1 Introduction .......................................................... 3
   2.2 Single-axle running gear with link suspension .............. 5
   2.3 Link suspension bogie .............................................. 6
   2.4 Y25 bogie ............................................................... 7
3 Running Behaviour of European Standard Freight Wagons .... 9
   3.1 Introduction .......................................................... 9
   3.2 Behaviour on tangent track ....................................... 9
   3.3 Behaviour in curves ................................................. 13
   3.4 Influence on track deterioration ................................. 15
4 The Present Work ........................................................... 17
   4.1 Introduction .......................................................... 17
   4.2 Link suspension characteristics ................................ 17
   4.3 Multibody dynamic simulation model ......................... 19
   4.4 Improved ride comfort ............................................ 21
   4.5 Influence on track deterioration ................................. 21
5 Conclusions and Future Work .......................................... 23
   5.1 Conclusions .......................................................... 23
   5.2 Future work ............................................................ 24
References ........................................................................ 27
Preface and acknowledgements

The work reported in this doctoral thesis has been carried out as part of a research programme on vehicle-track interaction (called SAMBA) at the Royal Institute of Technology (KTH), Division of Rail Vehicles. The aim of the present work is to investigate the dynamic performance of freight wagons.

The financial and personal support from the Swedish National Rail Administration (Banverket), Bombardier Transportation (Sweden), Green Cargo and Interfleet Technology (Sweden) is gratefully acknowledged.

For the on-track tests additional support was received from Green Cargo, Interfleet Technology, Kockums Industrier, Dellner Dampers and Tikab Strukturmekanik.

The support from Mr. Ingemar Persson at DEsolver regarding the multibody simulation software GENSYS is also gratefully acknowledged.

Thanks to Mr. Per-Erik Olsson for providing documents and background information on development of the standard running gear in ORE’s B37 group.

Special thanks to Mr. Kent Lindgren and Mr. Danilo Prelevic at the Marcus Wallenberg Laboratory for their valuable contribution to the laboratory tests.

Finally, I would like to thank my colleagues at the division, in particular my supervisors Dr.-Ing. Sebastian Stichel and Prof. Evert Andersson as well as Prof. Mats Berg.

Stockholm, June 2007

Per-Anders Jönsson
Abstract

The link suspension is the most prevailing suspension system for freight wagons in Central and Western Europe. The system design is simple and has existed for more than 100 years. However, still its characteristics are not fully understood. This thesis investigates the dynamic performance of freight wagons and comprises five parts:

In the first part a review of freight wagon running gear is made. The different suspension systems are described and their advantages and disadvantages are discussed.

The second part focuses on the lateral force-displacement characteristics of the link suspension. Results from stationary measurements on freight wagons and laboratory tests of the link suspension characteristics are presented. To improve the understanding of various mechanisms and phenomena in link suspension systems, a simulation model is developed.

In the third part the multibody dynamic simulation model is discussed. The previous freight wagon model developed at KTH is able to explain many of the phenomena observed in tests. In some cases, however, simulated and measured running behaviour differ. Therefore, a new simulation model is presented and validated against on-track test results. The performance of standard two-axle freight wagons is investigated. The most important parameters for the running behaviour of the vehicle are the suspension characteristics. The variation in characteristics between different wagons is large due to geometrical tolerances of the components, wear, corrosion, moisture or other lubrication. The influence of the variation in suspension characteristics and other parameters on the behaviour of the wagon, on tangent track and in curves, is discussed. Finally, suggestions for improvements of the system are made.

A majority of the traffic related track deterioration cost originates from freight traffic. With heavier and faster freight trains the maintenance cost is likely to increase. In the fourth part the possibility to improve ride comfort and reduce track forces on standard freight wagons with link suspension is discussed. The variation of characteristics in link suspension running gear is considerable and unfavourable conditions leading to hunting are likely to occur. Supported by on-track tests and multibody dynamic simulations, it is concluded that the running behaviour of two-axled wagons with UIC double-link suspension as well as wagons with link suspension bogies (G-type) can be improved when the running gear are equipped with supplementary hydraulic dampers.

Finally in the fifth part the effects of different types of running gear and operational conditions on the track deterioration marginal cost — in terms of settlement in the ballast, component fatigue, wear and RCF — is investigated. Considerable differences in track deterioration cost per produced ton-km for the different types of running gear are observed. Axle load is an important parameter for settlement and component fatigue. Also the height of centre of gravity has significant influence on track deterioration, especially on track sections with high cant deficiency or cant excess.

Keywords: railway; freight wagon; running gear; link suspension; laboratory test; stiffness; dry friction; hysteresis; simulation; vehicle-track interaction; multibody simulation; MBS.
Outline of Thesis

The scope of this thesis is the dynamic vehicle-track interaction of European standard freight wagons with link suspension. The thesis includes an introduction, a research review, a summary, and the following appended papers:


For all papers Jönsson has carried out the calculations, analysed the results and written the manuscript. The analyses and manuscripts have been discussed and reviewed by Andersson, Stichel respectively Persson. The experimental analysis of link suspension components in paper A was carried out by Jönsson. The data recording for the on-track tests in papers C, D and E was performed by Interfleet Technology AB. The on-track test was supervised by Andersson and Jönsson.
Contribution of Thesis

This thesis has improved the understanding of the link suspension system used in European railway freight wagons. Several features and phenomena, in the dynamic behaviour of freight wagons with lateral link suspensions, have been found and studied through laboratory tests, multibody dynamic simulations and on-track tests. Some of the features and phenomena are well known from earlier investigations, while others appear to be fairly unknown, or at least not made public. Suggestions for improvement of the dynamic performance of freight wagons are made as well.

The thesis is believed to make the following contributions to the present research field:

- A comprehensive literature review covering various freight wagon running gear designs is published.
- A new simulation model that improves the predictability for multibody dynamic simulations of freight wagons with link suspensions is proposed.
- The simulation results are validated against on-track test results.
- The variation in lateral respectively longitudinal suspension characteristics is quantified.
- It is shown that the risk of wheelset hunting is restricting the possibility to increase speed for empty two-axled freight wagons.
- It is found that for standard freight wagon running gear ride comfort can be improved and track forces reduced by means of supplementary hydraulic dampers.
- The influence of different types of running gear and operational conditions on the marginal track deterioration cost is investigated.
- The actual contact geometry of the links and end bearings is found to deviate considerably from the nominal geometry. This is the case for new components – due to geometrical tolerances – and for components worn in service. These deviations have a significant influence on the suspension characteristics.
- The influence of elastic deformation in the contact surfaces of links end bearings is pointed out to be essential for the system characteristics.
- Further more are flexibilities in the suspension components as well as in the connecting structures found to have considerable effect on the suspension characteristics.
- Generally, considerable variations in the hysteresis loops are shown to appear for different sets of suspension components.
1 INTRODUCTION

The railway system is complex. The dynamic response of a freight wagon strongly depends on the interaction between vehicle and track respectively vehicle and the transported goods. Main requirements for the technology used in freight transport systems are safety and cost efficiency. Due to the complexity with various conditions in different countries an introduction of new types of running gear or enhancement in operational conditions, i.e. increased axleload and speed, has to be made with great caution. The running gear on freight wagons used in international traffic have great uniformity. Three different principles, shown in Figure 1, are mainly used.

- Y25 bogie.
- Link suspension bogie (G-type).
- Two-axle wagons with UIC double link suspension.

Wagons with these types of running gear exist in large numbers and will continue to be the backbone of the European rail freight transport system for a foreseeable future.

Figure 1: Standard types of running gear.

The transportation effort on rail in Sweden has remained relatively constant since the beginning of the 1970s. During the same period has the road transportation effort increased considerably, cf. Figure 2. In Europe the loss of market share is even greater. Hence, improving ride quality and increase axleload, loading gauge and speed are desirable in order to make rail freight traffic more competitive [26] and [52].

However, a majority of the traffic related cost for track deterioration originates from freight traffic. As heavier and faster freight trains are introduced the cost for track maintenance is likely to increase, at least if freight wagons with standard running gear are used and the track is not strengthened.
Figure 2: Freight transport effort in Sweden and comparison of market share in Sweden, USA and Europe [52].
2 EUROPean freight wagon running gear

2.1 introduction

Early efforts were made to standardize European freight wagons. In 1947 the European Economic Commission gave the International Union of Railways (UIC) the initiative and they defined a European standardization programme with the following aims:

- Interchangeability of the most frequently required freight wagon components.
- Assimilation of some principle freight wagon data, in particular measures related to loading capacity of the wagons.
- Complete standardisation of freight wagons.

The European running gear designs for freight wagons in international traffic, and to large extent national operations as well, were given their main running characteristics during the 1950s and 1960s. Requirements for increased maximum operational speed in the forceable future, i.e. 30-40 years, were considered when the running characteristics were set [56].

Today freight wagons in Europe run typically at maximum 100 km/h with a maximum axle load of 22.5 tonnes. In Sweden a whole network for freight traffic with an increased loading gauge and 25 tonnes axle load (for some lines 30 tonnes or more) is built. The largest rail freight company, Green Cargo AB, is also running overnight mail service with specially equipped two-axle freight wagons at 160 km/h at a maximum axle load of 20 tonnes. Similar mail traffic exists in Germany and France.

Outside central and western Europe the so called three-piece bogie is the prevailing running gear design for freight wagons. Different variations of the three-piece design exist, for example the inter-axle linkage designs of Scheffel and List. Reviews of various three-piece bogie designs are given in [21] and [68]. More information on the three-piece bogies is given in [10], [22], [33], [36], [41], [45], [46], [48], [62], [67], [69] and [72]. A detailed review of freight wagon running gear in general is presented in a separate report by the author [29].

Since the middle of the 1990s several novel designs of freight wagon running gear are used in Europe. Most of these designs are, up to now, used in national freight operations only. These and traditional European designs are listed in Table 2-1. Reference to literature for further information is given. Traditionally friction damping is used on freight wagons. However, on some of the new running gear designs hydraulic dampers are used.

A short description of the double-link suspension, link bogie and Y25 bogie is given in Sections 2.2 - 2.4.
Section 2 - European Freight Wagon Running Gear

Table 2-1  Running gear for freight wagons in Europe [29].

<table>
<thead>
<tr>
<th>Running gear</th>
<th>Reference</th>
<th>Type</th>
<th>Primary damping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double-link suspension</td>
<td>[4], [23], [34], [35], [39], [44], [50], [74], [75]</td>
<td>Single-axle running gear</td>
<td>Friction</td>
</tr>
<tr>
<td>Link suspension bogie</td>
<td>[23], [43], [50], [73], [78]</td>
<td>Bogie</td>
<td>Friction</td>
</tr>
<tr>
<td>Y25</td>
<td>[16], [18], [25], [28], [43], [47], [50], [53], [73]</td>
<td>Bogie</td>
<td>Friction</td>
</tr>
<tr>
<td>Axle motion bogie</td>
<td>[1], [7]</td>
<td>Bogie</td>
<td>Friction</td>
</tr>
<tr>
<td>DRRS bogie</td>
<td>[51]</td>
<td>Bogie</td>
<td>Friction</td>
</tr>
<tr>
<td>Niesky link</td>
<td>[13], [14]</td>
<td>Single-axle running gear</td>
<td>Friction</td>
</tr>
<tr>
<td>TF25</td>
<td>[15], [20], [68], [71]</td>
<td>Bogie</td>
<td>Hydraulic</td>
</tr>
<tr>
<td>TF25SA</td>
<td>[63], [82]</td>
<td>Single-axle running gear</td>
<td>Hydraulic</td>
</tr>
<tr>
<td>Unitruck</td>
<td>[1], [42]</td>
<td>Single-axle running gear</td>
<td>Friction</td>
</tr>
<tr>
<td>Y37 bogie</td>
<td>[3], [12], [49], [51]</td>
<td>Bogie</td>
<td>Friction</td>
</tr>
<tr>
<td>Gigabox</td>
<td>[38]</td>
<td>Bogie</td>
<td>Hydraulic/Rubber</td>
</tr>
<tr>
<td>SCTE Barber Easy Ride</td>
<td>[70]</td>
<td>Bogie</td>
<td>Friction</td>
</tr>
<tr>
<td>ELH Opti-Track</td>
<td>[70]</td>
<td>Bogie</td>
<td>Friction</td>
</tr>
<tr>
<td>LEILIA bogie</td>
<td>[24], [26]</td>
<td>Bogie</td>
<td>Hydraulic/Rubber</td>
</tr>
</tbody>
</table>

The wheel-rail interface is important for the dynamic interaction between vehicle and track. In Europe there are different approaches on how the interface should be managed. Wheel and rail profiles and rail inclination differs from country to country, e.g.,

- 1 in 20 rail inclination - UK, France, Italy, Norway,
- 1 in 40 rail inclination - Germany, Austria, Switzerland,
- 1 in 30 rail inclination - Sweden.

For freight wagons in international traffic it is important that they are designed to perform well for all variable wheel-rail contact conditions that can occur. Due to wear
and maintenance operations the variation in contact conditions can be even greater. The equivalent conicity is often used to characterise the wheel-rail interface. In Figure 3 a comparison between the S1002 and P8 wheel profiles on rails with 1 in 20 respectively 1 in 40 inclination as well as the effect of variation in track gauge is shown. The equivalent conicity for the S1002 wheel profile on rails with 1 in 20 inclination can be low and can cause bad ride comfort for freight wagons. Contact geometry also determines the size of the contact patch and in turn the contact stresses which also are important for cost and safety of rail freight traffic.

Figure 3: Wheel-rail contact conditions. Comparison between S1002 and P8 wheel profiles on UIC60 rail profiles with various inclination.

2.2 Single-axle running gear with link suspension

Freight wagons with link suspensions have existed for more than 100 years. The link suspension, shown in Figure 4, is the most common suspension type for freight wagons in Europe today. Already in 1890 the principle of link suspension was defined as a standard on two-axle freight wagons [23]. The present design originates from the early 1950s. The parabolic leaf spring was introduced as a standard component and the permissible axle load was increased to 22.5 tonnes in the 1980s [44], [50].

The vehicle body is connected by double links to the parabolic or trapezoidal leaf spring that rests on the axle box. This arrangement allows the axle box to move in both the longitudinal and the lateral direction relative to the carbody [13], [14] and [23].

The suspension is quite simple and robust and also occupies a modest amount of space laterally and vertically. Stiffness and damping are both provided by one system and are intended to be proportional to the vertical load on the axle box. This type of running gear
is also quite light, which allows a maximum of payload in the wagon. It is also quite inexpensive. The lateral and the longitudinal play is approximately ±20 mm [44].

**Figure 4:** Single-axle running gear with UIC double-link suspension.

### 2.3 Link suspension bogie

The link suspension principle has been used on freight wagon bogies since about 1925. The bogie Type 931 was developed in the 1950s and had an axle distance of 2000 mm and wheel diameters of 1000 mm. The link suspension bogie, also known as the G bogie, was the first bogie to be standardized by UIC. The UIC standard for freight bogies was revised in 1966 to prepare for the introduction of automatic couplers. The new link suspension bogie design, known as the Talbot bogie and in Sweden also G66, has an axle distance of 1800 mm and 920 mm wheel diameters. Finally improvements in the design were made and the G70 type, and later on the G762, was introduced [43], [50]. The commonly used type G70 is shown in Figure 5. The lateral play is ±23 mm and the longitudinal play is ±6 mm [44].

**Figure 5:** Link suspension bogie (G70).
2.4 Y25 bogie

In 1960 the French National Railways (SNCF) started to develop a new type of freight wagon bogie. The bogie should be lighter and occupy less space than the standard bogie of those days, the link bogie Type 931 described in Section 2.3. The bogie known as Y21 was designed to be interchangeable with the Type 931 bogie. The Y21 bogie had an axle distance of 2000 mm and used wheels with a diameter of 920 mm. Due to the use of coil springs instead of leaf springs the bogie frame could be made shorter and lighter, [43] [47].

When the standard for freight wagon bogies were revised in 1966 the design was changed and the Y25 bogie was born. The Y25 bogie, shown in Figure 6, has an axle distance of 1800 mm and 920 mm wheel diameters.

The suspension of the Y25 bogie consists of coil springs and friction dampers. The vertical load that is carried by the outer coil springs located towards the bogie centre, is transmitted through the inclined Lenoir links connecting the bogie frame with the spring holders. The resulting longitudinal force on the spring holders depends on the vertical axle box load and is transmitted to the axle boxes by pushers. Thus friction forces, approximately proportional to the vertical load, are created in the friction surfaces between the axle boxes and the bogie frame via the pushers. As a result lateral and vertical motions are damped, [28], [43] and [53].

![Diagram of Y25 bogie](image)

**Figure 6:** Y25 bogie [28].

The shorter bogie frame together with the use of coil springs instead of leaf springs makes the Y25 bogie slightly lighter than the link suspension bogie. The lateral play of ±10 mm between the wheelsets and the bogie frame is less than half of the play for the link suspension bogie and the Y25 bogie therefore permits the wagon to have a
somewhat wider carbody. The longitudinal play is 4 mm [28]. However, the curving performance is poorer than for the link suspension bogie [75].
3 RUNNING BEHAVIOUR OF EUROPEAN STANDARD FREIGHT WAGONS

3.1 Introduction

The European standard running gear were, as discussed in Chapter 2, mainly developed during the 1950s and the 1960s. Traditionally the dynamic performance was investigated through on-track tests [56]. Due to the complex suspension characteristics analytic analyses were restricted to linearized models. During recent years, however, non-linear simulation models of standard freight wagon running gear are developed. In Section 3.2 and 3.3 some of these models are reviewed. Due to the wheel-rail contact forces the track will deteriorate. The major mechanisms that cause cost for track deterioration are:

- Track geometry degradation.
- Fatigue in components.
- Wear of the rails.
- Rolling contact fatigue, RCF.

Models for track deterioration are reviewed in Section 3.4.

Analysing the running behaviour of freight wagons is complex due to the large variations within the system. Stichel [76] pointed out the following three topics to be of special interest regarding the running behaviour of freight wagons with standard running gear:

- High vertical wheel-rail forces which might cause serious track deterioration.
- Non-satisfactory curving performance with high creep-forces, causing wear and fatigue problems.
- Suddenly arising violent hunting motions, sometimes at speeds far below the maximum operating speed.

3.2 Behaviour on tangent track

Railway vehicles are so called parameter dependent systems. A typical parameter is the vehicle speed \( v \) and the equilibrium solution to the system depends on the value of the parameter. As the system is non-linear several equilibrium solutions can exist for the same set of parameters. Hence, the equilibrium solution does not only depend on the parameters but initial conditions as well. Non-linear mechanics and its application to rail vehicle system dynamics is discussed by several authors, c.f. True [84]-[85], Stichel [80] and Polach [66]. A principle bifurcation diagram for a rail vehicle is shown in Figure 7. For speeds below \( v_{\text{lin}} \), the so called non-linear critical speed, only the equilibrium solution exists and any oscillations are damped out. However, if the speed is between \( v_{\text{cr}} \) and \( v_{\text{lin}} \) two stable attractors separated by an unstable branch exist. Here the response of the system depends on the initial conditions. If the initial conditions are above the unstable branch the equilibrium solution is given by the non-zero attractor. For speeds above \( v_{\text{lin}} \) the limit cycle is always reached regardless of the excitation amplitude.
Link suspension characteristics

The most important parameters for the running behaviour of the vehicle are the suspension characteristics. Lange developed a model for the horizontal suspension characteristics based on a geometrical representation of the components in the suspension [39] and [40].

Piotrowski investigated the lateral and longitudinal suspension characteristics [65]. He presented detailed models realised by a number of pivoted pendulums composing linkages. The detailed models were simplified to systems of dry-friction sliders and linear springs that reproduce the suspension characteristics.

The characteristics with worn suspension elements with non-cylindrical shape is investigated by Grzelak and Piotrowski [19]. They conclude that the geometry of the components in contact strongly influences the characteristics.

Y25 bogie

Several authors have investigated the running performance of the Y25 bogie [8], [16], [25], [28], [53] and [77]. Evans and Rogers compared simulated and measured running behaviour for an empty freight wagon with Y25 bogie [16]. They concluded that modelling of the secondary yaw suspension is particularly important. The longitudinal play in the sidebearers have significant influence on the running behaviour for the empty vehicle. The overall conclusion is that the simulation model predict the running behaviour well.

Stichel compared on-track test results with simulation results for an empty respectively loaded wagon [77]. He also concludes that the Y25 simulation model can represent most phenomena found in on-track tests.

Link suspension bogie

Stiepel and Zeipel analysed the performance of a freight wagon with link suspension bogie [81]. They measured suspension characteristics in a laboratory testrig and used the measure hysteresis loops in the simulation model.
A comparison between measured quantities and simulated behaviour is performed by Stichel [77] and [78]. He concludes that in many cases the measured and simulated behaviour of a freight wagon with link suspension bogies agree quite well. However, in some cases there are discrepancies that motivate further studies with more advanced simulation models.

**Two-axle wagon with link suspension.**

Hoffmann studied in his thesis the fundamental dynamic behaviour of two-axle freight wagons [27]. Special attention was paid to the formulation and numerical integration of the non-smooth problem. A bifurcation diagram for an empty two-axle freight wagon is shown in Figure 8. The diagram shows that the two-axle freight wagon has two principally different hunting modes, *wheelset hunting* and *carbody hunting*. At wheelset hunting the wheelsets move laterally from flange to flange. The wheelset hunting mode has a frequency in the range 4-8 Hz and is present at higher speeds. The frequency for the carbody hunting mode is lower, generally between 1.5 and 3 Hz.

*Lange developed a simulation model for two-axle freight wagons with link suspensions [39] and [40]. He also introduced a model for the horizontal suspension characteristics based on a geometrical representation of the components in the suspension.*

A comparison between measured quantities and simulated behaviour is performed by Stichel in [74] and [77]. He concludes as well for two-axle wagons with link suspensions that in many cases the measured and simulated behaviour agree quite well. However, in some cases there are discrepancies that have to be studied further.

In the early work of Stichel [76], the following aspects are set up for further investigations:

- The characteristics and change of characteristics of the link suspension with time. Perhaps also the modelling of the link suspension has to be improved.
- Realistic flexible eigenmodes of the carbody determined with help of FE-models have to be incorporated in the simulation models to investigate their influence on the running behaviour.
The nonlinear behaviour of the vehicles with dramatic changes of the vehicle response due to minimal changes in the input data has to be studied further, to get a better impression on how important this might be for the general running behaviour.

The importance of considering the structural flexibility of the carbody when analysing two-axle freight wagons is shown in [79]. Eigenmodes of the carbody underframe are calculated with finite element analysis. The lowest eigenmodes are shown in Figure 9. The first torsional eigenmode is for the loaded wagon 2.5 Hz and the four first eigenmodes are all below 10 Hz.

![Figure 9: Four first free eigenmodes for a loaded underframe [79]. 20.5 tonnes axleload. Frequencies for the empty vehicle is shown in parentheses.](image)

The sensitivity in the response to small parameter variations at typical operational speeds is analysed by Stichel [80]. The reason for the observed behaviour is the co-existence of two stable attractors, in principle shown in Figure 7, for a relatively wide speed range. Large single track irregularities can change the behaviour from a violent hunting motion to just a reaction to track irregularities or the other way around.

The influence of high vertical track forces on track geometry degradation is investigated by Stichel [75]. He concludes that further research on this topic is important because the
cost for track maintenance is considerable and that a large amount of the cost originates from freight traffic. Further more wear and fatigue in curves are probably not a major issue on most main lines in Europe, because the average curve radius is large. In some countries, however, with a considerable amount of small radii curves, the curving performance of freight wagons is not negligible.

### 3.3 Behaviour in curves

Specht calculated the material loss on the wheels for three types of freight wagon running gear, the Y25 bogie, the link suspension bogie (DB665) and the three-piece bogie with inter-axle linkage by Sheffel (SATS) [73]. The contact patch is discretized and energy dissipation is calculated for different running conditions. Then the material loss off the wheels is determined. The relation between energy dissipation and material loss is determined trough roller rig tests. In Figure 10 is the material loss after 10000 km on a typical railway network shown. The curve radii distribution used in this comparison is:

<table>
<thead>
<tr>
<th>Radius</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tangent</td>
<td>60 %</td>
</tr>
<tr>
<td>2000 m</td>
<td>14 %</td>
</tr>
<tr>
<td>750 m</td>
<td>11 %</td>
</tr>
<tr>
<td>500 m</td>
<td>10 %</td>
</tr>
<tr>
<td>300 m</td>
<td>5 %</td>
</tr>
</tbody>
</table>

The difference between the Y25 bogie and the link suspension bogie (DB665) is considerable. Block breaking influences the tread wear and the effect on the total worn off volume is relatively larger for running gear with soft wheelset guidance due to their better curving performance. For rails, however, only the curving performance contributes. Hence, here the difference between the different running gear is greater.

Stichel compared the quasistatic curving performance for the Y25 bogie, link suspension bogie and two-axle wagons with link suspensions [75]. The energy dissipation and angle of attack as function of curve radius is shown in Figure 11. The wagon with link suspension bogie steers almost perfect down to a curve radius of about 300 metres while the Y25 bogie steers radially down to a curve radius of 600 metre. On a railway network with many sharp curves this difference might not be intelligible.
Figure 10: Material loss on wheels. Contribution from breaking respectively wheel-rail contact on a typical railway network after 10000 km [73].

Figure 11: Yaw angle (angle of attack) of first wheelset and energy dissipation of first outer wheel for different curve radii [75].
Also the dynamic curving can be critical. Hunting can cause high track forces, especially when the lateral bump stops come in contact [74] and [78].

Pascal investigated the cause for derailments of UIC standard freight wagons Litt: G69, i.e. closed two-axle freight wagons with 5.7 meter distance between the wheelsets. Both theoretical and experimental work was performed. He concluded that the reason for the derailments was a combination of vehicle and track parameters. With new suspension components, i.e. low amount of hysteresis in the lateral suspension and a lateral amplitude of the wheelset of more than 15 mm the conditions can become hazardous. He also found that the system can be sensitive to initial conditions. In fact it was impossible to reproduce the same signal twice during on-track tests.

### 3.4 Influence on track deterioration

Increasing axleload, loading gauge and speed is desirable for rail freight operators in order to improve their competitiveness. However, by doing so the cost for maintaining the track is likely to increase. At least if not the running performance of the freight wagons are improved or the track strengthened. Hence, understanding the vehicle-track interaction is important in order to epitomize the rail transport system. Numerous models have been developed in order to analyse various aspects of track deterioration. A good overview of existing models is given by Öberg [92]. A few of these models are reviewed in this section.

During the 1980s ORE investigated the effect of increased axleload on cost for track maintenance. Tests were performed to study the effect of an increased permissible axleload from 20 to 22.5 tonnes. The proposed model couples traffic volume and track forces to track geometry degradation and component fatigue.

Based on research in the UK the Rail Surface Damage model is proposed [9]. This model considers the tangential forces in the contact patch and their influence on wear and rolling contact fatigue (RCF). The product between creep force and creepage, the so-called wear number, is calculated. Through damage identification and multibody simulations of the most common vehicles on the railway network the wear number is coupled to the size of damage on the track. For small wear numbers RCF is the dominating mechanism. As the wear number increases, wear becomes more prominent.

On the Swedish rail network the cost for track maintenance is mainly given by the four components:

- track geometry degradation,
- component fatigue,
- wear of the rails,
- rolling contact fatigue.

Öberg proposed a model mainly based on the ORE model and the Rail Surface Damage model. The model considers the cost caused by each of the four deterioration mechanisms and is calibrated against the cost for maintenance on the Swedish railway network. Hence, the model give a basis to evaluate different types of running gear and their effect on the cost for track maintenance. This model is choose for the study presented in Paper F.
4 THE PRESENT WORK

4.1 Introduction

In Chapter 3 the present knowledge in the research field was reviewed. Despite several studies on the area there is a need to better understand the behaviour of link suspension running gears and several questions are still to be answered, for instance:

- Is it possible to improve the predictability for multibody dynamic simulations?
- What are the variations in link suspension characteristics?
- How does the variation influence the dynamic performance of freight wagons.
- What are the limitations with the suspension system with regard to increased speed, axleload and loading gauge?
- Is it possible to improve the system?
- What are the influence of the dynamic performance on the track deterioration?

The link suspension characteristics is mainly discussed in Paper A, but to some extent also in Papers C and D.

The multibody dynamic simulation model is covered in Papers B-D. Paper D is basically a summary of Paper C.

The possibility to improve the dynamic performance is discussed in Paper E. Suggestions of general improvements to the system are given in Papers C and D.

The dynamic performance of the link suspension running gears is compared with the Y25 bogie in Paper F and the influence on track deterioration is discussed.

In Sections 4.2-4.5 the general content of the appended Papers A-F is summarized. Conclusions are presented in Chapter 5.

4.2 Link suspension characteristics

The most important parameters for the running behaviour of a vehicle are the suspension characteristics. Characteristics of the link suspension is therefore investigated through experimental and theoretical analysis of suspension components respectively measurements of lateral and longitudinal suspension characteristics of several freight wagons with link suspension. Suspension characteristics measurements from other sources are gathered as well.

In the experimental and theoretical part in Paper A, the influence of load, displacement amplitude, frequency and maintenance status of the components on the suspension characteristics is investigated. The experiment is not primary setup to measure force-displacement characteristics in a complete primary suspension as they are configured on a wagon. Rather the principal behaviour of the link suspension, in particular the contact between link and end bearing, is studied.

A principle hysteresis loop is shown in Figure 12. In Table 1 typical values for lateral and longitudinal characteristics are defined. Case 1, 3 and 5 respectively refer to min, average and maximum hysteresis loops found in measurements on wagons. The hysteresis loops are in principle changed according to Figure 13 as the suspension
components are worn. Hence, in lateral direction the hysteresis increases and longitudinally the hysteresis decreases.

**Figure 12:** Principle force-displacement characteristics.

**Figure 13:** Change in lateral respectively longitudinal characteristics due to wear of suspension components.
Table 1: Typical longitudinal and lateral suspension characteristics for 2-axle freight wagons with link suspension. Stiffness and force are defined in Figure 12. The values are normalized with the vertical axle box load.

<table>
<thead>
<tr>
<th>Case i</th>
<th>$k_x/F_{box}$ [1/m]</th>
<th>$k_y/F_{box}$ [1/m]</th>
<th>$F_d/F_{box}$ [1]</th>
<th>$k_x/F_{box}$ [1/m]</th>
<th>$k_y/F_{box}$ [1/m]</th>
<th>$F_d/F_{box}$ [1]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.0</td>
<td>6.0</td>
<td>0.04</td>
<td>20.0</td>
<td>3.0</td>
<td>0.08</td>
</tr>
<tr>
<td>2</td>
<td>10.0</td>
<td>6.0</td>
<td>0.05</td>
<td>27.0</td>
<td>3.0</td>
<td>0.09</td>
</tr>
<tr>
<td>3</td>
<td>20.0</td>
<td>6.0</td>
<td>0.06</td>
<td>35.0</td>
<td>3.0</td>
<td>0.10</td>
</tr>
<tr>
<td>4</td>
<td>30.0</td>
<td>6.0</td>
<td>0.08</td>
<td>45.0</td>
<td>3.0</td>
<td>0.10</td>
</tr>
<tr>
<td>5</td>
<td>40.0</td>
<td>6.0</td>
<td>0.10</td>
<td>55.0</td>
<td>3.0</td>
<td>0.11</td>
</tr>
</tbody>
</table>

4.3 Multibody dynamic simulation model

The previous freight wagon model developed at KTH is able to explain many of the phenomena observed in tests. In some cases, however, simulated and measured running behaviour differ. Therefore, a new simulation model, shown in Figure 14, is presented. Simulation results and on-track test results agree well. Hence, the model represents reality quite well.

The longitudinal dimension of the leafspring is considered by attaching the lateral elements between carbody and leafspring a distance $a_{al}$ from axle centre. A friction coupling connects the wheelset and leafspring in yaw. This was not considered in the previous model and the difference in running behaviour between the two models is considerable.

Figure 14: Coupling between the wheelset and carbody in the horizontal plane.
Investigating the dynamic behaviour of standard two-axle freight wagons shows that the most important parameters for the running behaviour of the vehicle are the suspension characteristics. Variation in characteristics between different wagons is large due to geometrical tolerances of the components, wear, corrosion, moisture or other lubrication. The influence of the variation in suspension characteristics on the dynamic performance is considerable. The variation in critical speed can be as much as ±20 km/h.

There are two principle different hunting modes for these types of wagons,

- wheelset hunting (usually in the frequency range 4-8 Hz),
- carbody hunting (usually in the frequency range 1.5-3 Hz).

However, carbody hunting can be caused by a resonance with several carbody eigenmodes,

- carbody yaw,
- symmetric lower sway,
- anti-symmetric lower sway.

The flexible carbody has a strong influence on the running behaviour of loaded wagons. The frequency of the carbody yaw eigenmode is decreased when flexible properties of the carbody is considered. Further more the torsional flexibility allows a hunting motion pattern where the trailing and leading wheelsets move independently, the anti-symmetric lower sway.

For the loaded wagon it is generally carbody hunting that causes unfavourable ride conditions, at least at normal operational speeds. Carbody hunting causes increased track forces and ride discomfort. At high conicity wheelset hunting can occur for speeds above 140-150 km/h.

For empty wagons carbody hunting occurs at lower speeds than for the loaded wagon. Since the track forces are low and it is generally not safety critical, other than under special conditions, it may be acceptable. However, for the empty wagons wheelset hunting can occur at speeds around current operational speeds on track with low as well as high conicity. To increase speed is not advisable without improving the suspension.

The quasistatic curving performance of two-axle freight wagons with link suspension is good due to the relatively low pendulum stiffness. Radial steering down to curve radii of 300 metre is possible under favourable conditions.

The primary suspension model for link suspension running gear is implemented in a simulation model for a two-axle freight wagon. The model can be used for bogie wagons with link suspensions as well. Implementing the model in a bogie vehicle has not been a part of the present work. Hence, simulations of quasistatic curving behaviour for the link suspension bogie in Paper F is performed with the previous model. However, the differences in quasistatic curving behaviour between the new and previous model are small.
4.4 Improved ride comfort

The variation of characteristics in link suspension running gear is, as discussed in Section 4.2, considerable and unfavourable conditions leading to hunting are likely to occur. If the variation in characteristics can not be controlled within closer limits supplementary means are needed in order to secure and improve ride qualities.

In this section the possibility to improve ride comfort and reduce track forces on standard freight wagons with link suspension is discussed. In Figure 15a) is a supplementary lateral and yaw-damper arrangement on a two-axled wagon shown. Lateral carbody accelerations from three tests are shown in Figure 15b). The original wagon is hunting at 100 km/h resulting in high lateral acceleration levels. With supplementary hydraulic dampers the running performance is considerably improved. The ride comfort at 160 km/h can be better than for the original configuration at 100 km/h.

Supported by on-track tests and multibody dynamic simulations it is concluded that the running behaviour of two-axle wagons with UIC double-link suspension as well as wagons with link suspension bogies (G-type) can be improved when the running gear are equipped with supplementary hydraulic dampers.

![Figure 15: a) Lateral damper and yaw-damper arrangement on a two-axled wagon. b) Test results. Lateral carbody acceleration. Comparison between original wagon at 100 km/h and configuration with hydraulic lateral and yaw-damper at 100 km/h respectively 160 km/h.](image)

4.5 Influence on track deterioration

Running characteristics of a railway vehicle, i.e. track forces and steering capability, affect the cost for track maintenance. One indicator of the steering capability is the energy dissipation in the contact patch. In Figure 16 is the energy dissipation on the leading outer wheels shown. The curving performance of link suspension running gear are good, however, on a railway network with many sharp curves the curving performance of a standard Y25 bogie is not sufficient.
Section 4 - The Present Work

Figure 16: Energy dissipation on leading outer wheel.

The marginal track deterioration cost, on railway network representable for freight traffic in Sweden, is calculated with a model developed by Öberg [92]. The curve radii distribution used in this comparison is:

<table>
<thead>
<tr>
<th>Radius</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tangent</td>
<td>62.0 %</td>
</tr>
<tr>
<td>1500 m</td>
<td>11.6 %</td>
</tr>
<tr>
<td>1200 m</td>
<td>8.6 %</td>
</tr>
<tr>
<td>750 m</td>
<td>13.9 %</td>
</tr>
<tr>
<td>500 m</td>
<td>2.8 %</td>
</tr>
<tr>
<td>320 m</td>
<td>1.1 %</td>
</tr>
</tbody>
</table>

In Figure 17 is the marginal track deterioration cost per ton-km shown. The cost is normalized with the total cost for the Y25 bogie. The total track deterioration cost per ton-km is 30%-40% lower for the vehicles with link suspension than for the wagon with Y25 bogie. Cost for wear and RCF is considerably higher for the Y25 bogie. The stiffer primary suspension of the Y25 bogie causes higher amount of RCF damage in large radius curves respectively wear in small radius curves.

Figure 17: Track deterioration cost normalized with the total cost for the Y25 bogie.
5 CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

Simulation results with the presented new model for two-axle freight wagons with UIC link suspension agree well with on-track test results. Hence, the model represents reality quite well, at least in the frequency range up till 15-20 Hz. The new model approach has considerable influence on the running behaviour. For the loaded wagon the critical speed is increased by up to 50% compared to the old model.

The most important parameters for the running behaviour are the suspension characteristics. At the same time the variation in the lateral and longitudinal suspension characteristics is considerable. The reasons for the variation are differences in contact conditions between link and bearing caused by geometrical tolerances of the components, wear, corrosion, moisture or other lubrication. The influence of the variations in suspension characteristics on the dynamic performance of two-axle freight wagons is considerable. The variation in critical speed can be as much as ± 20 km/h depending on the suspension characteristics.

There are two principle different hunting modes for these types of wagons,

- wheelset hunting (usually in the frequency range 4-8 Hz),
- carbody hunting (usually in the frequency range 1.5-3 Hz).

However, carbody hunting can be caused by a resonance with several carbody eigenmodes,

- carbody yaw,
- symmetric lower sway,
- anti-symmetric lower sway.

The flexible carbody has a strong influence on the running behaviour of loaded wagons. The frequency of the carbody yaw eigenmode is decreased when flexible properties of the carbody is considered. Further more the torsional flexibility allows a hunting motion pattern where the trailing and leading wheelsets move independently, the anti-symmetric lower sway.

For the loaded wagon it is generally carbody hunting that causes unfavourable ride conditions, at least at normal operational speeds. Carbody hunting causes increased track forces and ride discomfort. At high conicity wheelset hunting can occur for speeds above 140-150 km/h.

For empty wagons carbody hunting occurs at lower speeds than for the loaded wagon. Since the track forces are low and it is generally not safety critical, other than under special conditions, it may be acceptable. However, for the empty wagons wheelset hunting can occur at speeds around current operational speeds on track with low as well as high conicity. To increase speed is not advisable without improving the suspension.

The quasistatic curving performance of two-axle freight wagons with link suspension is good due to the relatively low pendulum stiffness. Radial steering down to curve radii of 300 metre is possible under favourable conditions.
The vertical damping force in the trapezoidal leaf spring is high. Hence, the vertical stiffness is for small amplitudes high which leads to high vertical track forces and bad ride comfort.

It is possible to considerably improve the running behaviour of standard freight wagons with link suspension running gear with supplementary hydraulic dampers. The ride comfort is improved and the vertical as well as lateral track forces are reduced. The flexible properties of the freight wagon underframe are important for the running behaviour as well as the characteristics of the suspension. As was shown for the two-axle wagon both yaw-dampers and lateral dampers are needed to achieve satisfactory running behaviour for all wheel-rail contact conditions. On low conicity carbody hunting is the dominant oscillation pattern. To reduce this motion lateral dampers between carbody (or bogie) and wheelset are needed. At high conicities only the wheelset is hunting. The hunting frequency is significantly higher as for carbody hunting. Here only wheelset (or bogie) yaw damping efficiently suppresses the oscillations. If the stiffnesses in the primary suspension are too low the possible improvement by adding dampers is limited. In this case satisfactory dynamic vehicle behaviour cannot be achieved.

It is concluded that the traffic induced marginal cost differs considerably between wagons with Y25 bogie, link bogie and 2-axle freight wagons with link suspension. The cost per ton-km is 30%-40% lower for wagons with link suspension. On a railway network with many sharp curves the worse curving performance of the standard Y25 bogie will have significant influence on the maintenance cost.

Axleload is probably the most important parameter for settlement and component fatigue. At 25 tonnes axleload the track deterioration cost is 20-30% higher compared to the reference case with 22.5 tonnes axleload.

The quasistatic load redistribution between high and low rail is considerable for wagons with high centre of gravity running at high cant deficiency. The higher deterioration cost induced has to be kept in mind when increasing the height and size of the loading gauge for freight wagons.

5.2 Future work

The wheel-rail interface can be improved from a national Swedish perspective. The S1002 wheel profile is optimised for 1:40 rail inclination and the P8 profile for a rail inclination of 1:20. In Sweden the track is laid with a rail inclination of 1:30. It should be possible to develop a wheel profile that is better adapted to this condition. The wheel-rail interface is also an important issue from a European perspective, e.g. for a freight wagon going from Germany to France, cf. Figure 2.

With enhanced wheel-rail contact geometry, i.e. initially a slightly higher conicity then today, and sharpened requirements for maintenance of the suspension components the ride comfort for loaded wagons can probably be improved.

Today wheelset hunting limits the possibility to increase speed of empty wagons. If new materials are introduced in the suspension components, that are resistant to wear and give more precise friction behaviour, the suspension characteristics can be designed more precisely. Then the variation of suspension characteristics would be less over the life span of the suspension components. With increased initial stiffness and damping in
the links the critical speed is increased. As long as the longitudinal pendulum stiffness is kept at today's level the influence on the curving performance would be moderate, the good curving performance would remain.

With increased utilization of the railway network the deterioration rate is likely to increase. However, the deterioration rate can be kept constant or even reduced by using a strengthened track design i.e. a heavier type of rail, larger sleepers and shorter sleeper spacing. The track forces can be reduced building special freight lines avoiding large cant deficiency or cant excess. With smaller track irregularities the dynamic contribution to the track forces can be reduced.

The dynamic contribution of the vertical track forces is of considerable magnitude. Freight wagons with UIC standard running gear exist in vast numbers. Finding cost effective solutions to improve the running behaviour in order to improve ride comfort and reduce the wheel-rail contact forces is important to improve transport quality and reduce maintenance cost.

In Europe 2-axle freight wagons are widely used. In Sweden a freight network with increased loading gauge and axle load is built up. The effect of traffic with 2-axle freight wagons operating at high axle load should be further investigated.

Recently some novel freight wagon running gear designs have been introduced in Europe. The influence of a larger introduction of these types on the transport cost should be investigated as a basis for future investment in freight wagons.
Section 5 - Conclusions and Future Work
REFERENCES


[13] **ERRI**: Dynamic behaviour of two-axled wagons for a 22.5 t axelload and a wheelbase of less than 8 m, for speeds of 100 and 120 km/h, Question B12 Report 67, 1997.
References


References


[42] **Meridian Rail Europe:** Track friendly freight bogies for 25 t axle load, UIC seminar, Frankfurt, 2002.


[49] **Müller L.:** Konzepte für Güterwagenlaufwerke für Geschwindigkeiten über 120 km/h, Eisenbahntechnische Rundschau 37, 1988, p 799-802.


Dynamic Vehicle-Track Interaction of European Standard Freight Wagons
with Link Suspension


[57] ORE B56/Rp2: Improvement of the running stability of existing RIV wagons required to run under any loading conditions at speeds of 80 km/h, ORE, Utrecht, March 1967.


References


References