



KTH Aeronautical
and Vehicle Engineering

Modelling and Laboratory Investigations on Freight Wagon Link Suspensions with respect to Vehicle-track Dynamic Interaction

by

Per-Anders Jönsson

Licentiate Thesis

TRITA AVE 2004:48
ISSN 1651-7660
ISBN 91-7283-806-X

Postal Address

Royal Institute of Technology
Aeronautical and Vehicle Engineering
Railway Technology
SE-100 44 Stockholm

Visiting address

Teknikringen 8
Stockholm

Telephone

+46 8 790 84 76

Fax

+46 8 790 76 29

E-mail

mabe@kth.se

*Modelling and Laboratory Investigations on Freight Wagon Link Suspensions
with respect to Vehicle-Track Dynamic Interaction*

Contents

Preface and acknowledgements	iii
Abstract	v
Outline of Thesis	vii
Contribution of Thesis	ix
1 Introduction	1
2 Freight Wagon Running Gear in Europe	1
2.1 Single-axle running gear with link suspension	2
2.2 Link suspension bogie	3
2.3 Y25 bogie	4
3 Link Suspension Characteristics	5
4 Laboratory Tests and Theoretical Analysis	6
5 Improved Ride Qualities	8
6 Conclusions and Further Work	11
References	13

*Modelling and Laboratory Investigations on Freight Wagon Link Suspensions,
with respect to Vehicle-track Dynamic Interaction*

*Modelling and Laboratory Investigations on Freight Wagon Link Suspensions,
with respect to Vehicle-track Dynamic Interaction*

Preface and acknowledgements

The research reported in this thesis has been carried out as a part of a research program on vehicle-track interaction (called SAMBA) at the Royal Institute of Technology (KTH), Division of Railway Technology. The aim of the present work is to investigate the dynamic performance of freight wagons with existing running gear and to suggest improvements.

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

Special thanks to Mr. Kent Lindgren and Mr. Danilo Prelevic at the Marcus Wallenberg Laboratory for their valuable contribution to the laboratory tests. The support from Mr. Ingemar Persson at DEsolver regarding the simulation software is also gratefully acknowledged.

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

Stockholm, November 2004

Per-Anders Jönsson

*Modelling and Laboratory Investigations on Freight Wagon Link Suspensions,
with respect to Vehicle-track Dynamic Interaction*

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 emphasizes freight wagon dynamics and comprises three 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 review covers the running gear standardized by UIC and the conventional so-called three-piece bogie. Additionally five improved three-piece bogies and twelve novel running gear designs are presented.

The second part focuses on the lateral force-displacement characteristics in the link suspension. Results from stationary measurements on freight wagons and laboratory tests of the link suspension characteristics are presented. To improve understanding of the various mechanisms and phenomena in link suspension systems a simulation model is developed. Link suspension systems have strongly nonlinear characteristics including a hysteresis loop. The loop exhibits usually three characteristic sections with different tangential stiffnesses. The actual contact geometry of the links and end bearings has a significant influence on the characteristics. By wear in ordinary service - as well as by geometric tolerances on new components - the contact geometry may deviate considerably from nominal geometry. Further, it seems that elastic deformation in the contact surfaces has considerable effects on the suspension characteristics, in particular on the initial rolling stiffness for small displacements. Also, flexibilities in links and end bearings influence the characteristics. It is also observed that new components after a short period of dynamic testing can exhibit a very low amount of energy dissipation, a phenomenon that is also indicated in some stationary measurements on wagons.

To summarize the second part, it appears that the link suspension characteristics are very sensitive to several factors being hard to control in the real world of freight wagon operations. The various stiffnesses and hysteresis loops have a considerable variation and may have a strong influence on the ride qualities of vehicles. As long as the characteristics can not be controlled within closer limits than found in this study, there is a strong need for sensitivity analysis to be made, both in predictive multibody simulations of vehicle dynamics, as well as in verification and acceptance tests.

In the third part a study on the possibility to improve ride qualities of freight wagons with link suspensions is presented. Parametric studies with multibody dynamic simulations on freight wagons equipped with link-suspension bogies are performed. The effect of supplementary friction and hydraulic damping is investigated under various running conditions: speed, loading, tangent and curved track, wheel-rail contact geometry, track gauge and track irregularities. Substantial improvements of the lateral running behaviour of wagons with link suspension bogies can be achieved - both at ordinary speeds and at increased speeds - by using a proper combination of supplementary hydraulic dampers. Speeds up to 160 km/h could be realistic.

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

*Modelling and Laboratory Investigations on Freight Wagon Link Suspensions,
with respect to Vehicle-track Dynamic Interaction*

*Modelling and Laboratory Investigations on Freight Wagon Link Suspensions,
with respect to Vehicle-track Dynamic Interaction*

Outline of Thesis

The scope of this thesis is freight wagon performance with respect to vehicle-track dynamic interaction. The thesis includes an introduction which summarises a **literature review** [17], and the following appended papers:

- A** Jönsson, P-A.: *Experimental and Theoretical Analysis of Freight Wagon Link Suspension*. Partly presented at the XXI International Congress of Theoretical and Applied Mechanics, Warsaw, Poland, August 15-21, 2004.
To be submitted for publication.

- B** Jönsson, P-A. and Andersson, E.: *Influence of Link Suspension Characteristics on Freight Wagon Lateral Dynamics*. Presented at the 6th International Conference on Railway Bogies and Running Gear, Budapest, Hungary, September 13-16, 2004.
To be published in the conference proceedings.

Both papers have been written by Per-Anders Jönsson and reviewed by Prof. Evert Andersson and Prof. Mats Berg. The above mentioned part of Paper A was presented with Dr. Sebastian Stichel as co-author at the XXI International Congress of Theoretical and Applied Mechanics.

*Modelling and Laboratory Investigations on Freight Wagon Link Suspensions,
with respect to Vehicle-track Dynamic Interaction*

Contribution of Thesis

This thesis has improved the understanding of the link suspension system used in European railway freight wagons. Several features and phenomena of lateral link suspensions have been found and studied in laboratory tests and in a simulation model developed for this purpose. 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.
- 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 is pointed out to be essential for the system characteristics.
- Flexibilities in the suspension components as well as in the connecting structures are found to have a considerable effect on the suspension characteristics.
- A higher amount of energy dissipation is found in laboratory dynamic tests at 1-3 Hz compared to tests at 0.1 Hz.
- New suspension components appear to exhibit a very low amount of energy dissipation after a short period of dynamic testing.
- Generally, considerable variations in the hysteresis loops are shown to appear between different sets of suspension components.
- Multibody simulations on vehicle-track interaction indicate possibilities for substantial improvements of vehicle dynamic performance for freight wagons equipped with standardized link suspension bogies. This is proposed to be achieved by means of supplementary hydraulic dampers.

*Modelling and Laboratory Investigations on Freight Wagon Link Suspensions,
with respect to Vehicle-track Dynamic Interaction*

1 INTRODUCTION

Most of the designs for running gear used on today's rail freight wagons in central and western Europe originated in the 1950s and 1960s. To increase competitiveness of freight traffic on rails it is desired to increase speed or axle load but this would - at least in some operational conditions with standard running gear - mean to exceed existing limit values for ride quality and wheel-rail forces. At least as important is to improve ride qualities in order to reduce damages on transported goods and being able to attract customers that require transport service for sensitive and high-value goods.

The European freight wagon designers have been guided by the principle that the wagons must be capable of being used on all standard-gauge railway networks in Europe. 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.

In line with these efforts to create and maintain a standard within UIC the term "freight wagon running gear" was for a long time - at least for international traffic - equal to either the single-axle link suspension, the link bogie or the Y25 bogie [1], [2]. These designs are presented in Section 2.

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 exist in Germany and France as well.

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 [3] and [4]. More information on the three-piece bogies is given in [5]-[16]. A detailed review of freight wagon running gear in general is presented in a separate **report by the author [17]**.

2 FREIGHT WAGON RUNNING GEAR IN EUROPE

Since the middle of the 1990s several novel designs of freight wagon running gear are used in Europe. Most of these designs are, up till now, used on national rail networks 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

Section 2 - Freight Wagon Running Gear in Europe

freight wagons. However, on some of the new running gear designs hydraulic dampers are used.

Table 2-1 *Running gear for freight wagons in Europe [17]. The first three types are standardized by UIC [1] and [2].*

Running gear	Reference	Type	Damping
Double-link suspension	[18]-[24]	Single-axle running gear	Friction
Link suspension bogie	[18], [20], [22], [25], [26]	Bogie	Friction
Y25	[20], [25]-[33]	Bogie	Friction
Axle motion bogie	[34], [35]	Bogie	Friction
DRRS bogie	[36]	Bogie	Friction
Niesky link	[37], [38]	Single-axle running gear	Friction
S2000	[37], [38]	Single-axle running gear	Friction
TF25	[4], [39], [40] [41]	Bogie	Hydraulic
TF25SA	[42], [43]	Single-axle running gear	Hydraulic
Unitruck	[34], [44]	Single-axle running gear	Friction
Y37 bogie	[36], [45], [46], [47]	Bogie	Friction

A thorough description of the running gear listed in Table 2-1 is given in [17]. A short description of the running gear standardized by UIC is given in the following Sections 2.1 - 2.3.

2.1 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 1, 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 [18]. 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 [19], [20].

The vehicle body is connected by double links to the parabolic or trapezoidal leaf spring that rests on the axle box. In some cases [18], [37], [38] single links with the same total link length are used. This arrangement allows the axle box to move in both the longitudinal and the lateral directions relative to the carbody.

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 is

*Modelling and Laboratory Investigations on Freight Wagon Link Suspensions
with respect to Vehicle-Track Dynamic Interaction*

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 [19].

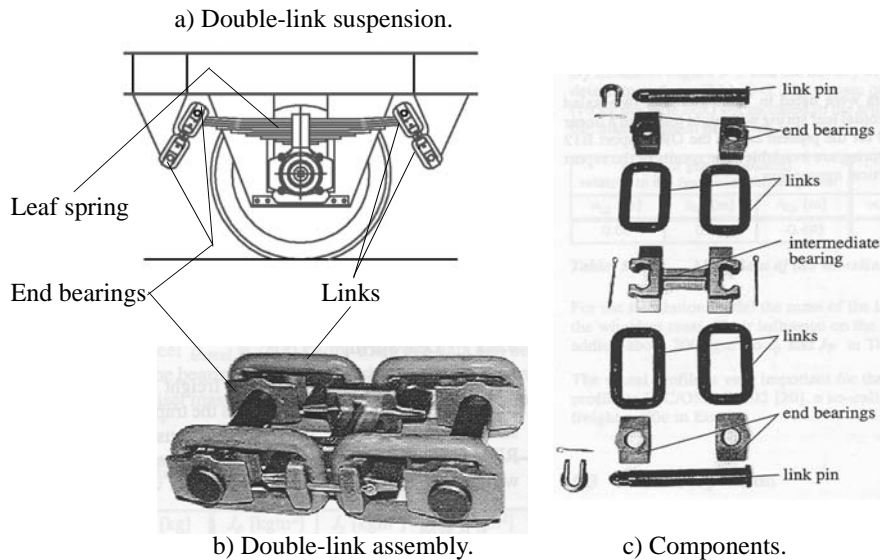


Figure 1: Single-axle running gear with UIC double-link suspension.

2.2 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 [20], [26]. The commonly used type G70 is shown in Figure 2. The lateral play is ± 23 mm and the longitudinal play is ± 6 mm [19].

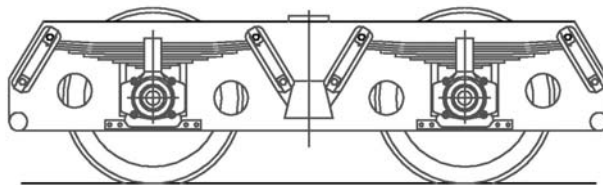


Figure 2: Link suspension bogie (G70).

2.3 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 2.2. 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, [26] [27].

When the standard for freight wagon bogies was revised in 1966 the design was changed and the Y25 bogie was born. The Y25 bogie, shown in Figure 3, 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, are 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, [26],[28] and [29].

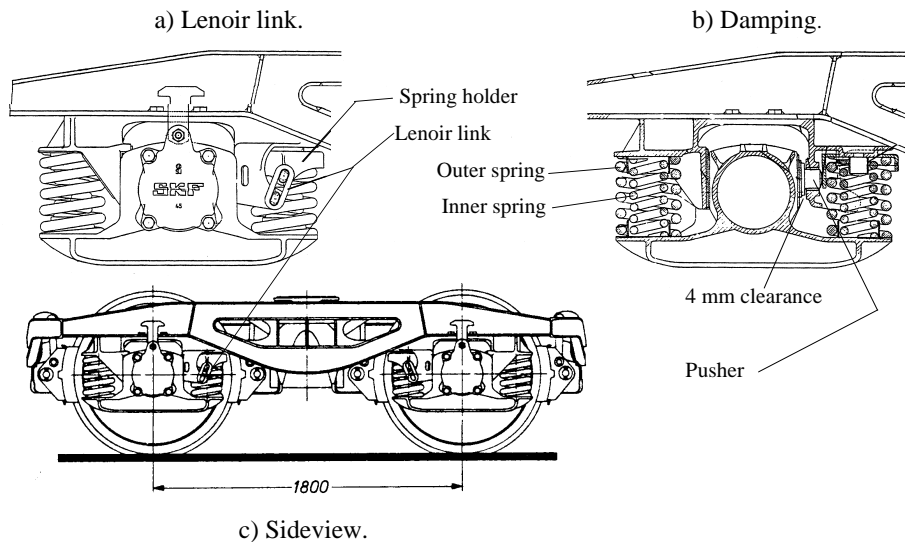


Figure 3: Y25 bogie [29].

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 [29]. However, the curving performance is poorer than for the link suspension bogie [21].

3 LINK SUSPENSION CHARACTERISTICS

The dynamic characteristics of a freight wagon, e.g. ride qualities and dynamic wheel-rail forces, are strongly dependent of the suspension characteristics. Link suspensions in freight wagons have principally a similar mode of operation in lateral and longitudinal directions. In the present work the lateral characteristics are investigated. Suspension characteristics from previous stationary tests are looked into, laboratory tests are performed, and the results are presented and discussed, see **Paper A**.

Stationary force-displacement characteristics for freight wagon suspension system are known from a number of sources, for example [21], [23], [48] of which a sample is shown in Figure 4.

We observe the typical non-linear behaviour with a considerable hysteresis. The variation of characteristics between different cases is significant. The variations mainly appear in the initial tangential stiffness, i.e. for small displacements, and in the size of the hysteresis loop. Variations would probably be even larger if more wagons were studied.

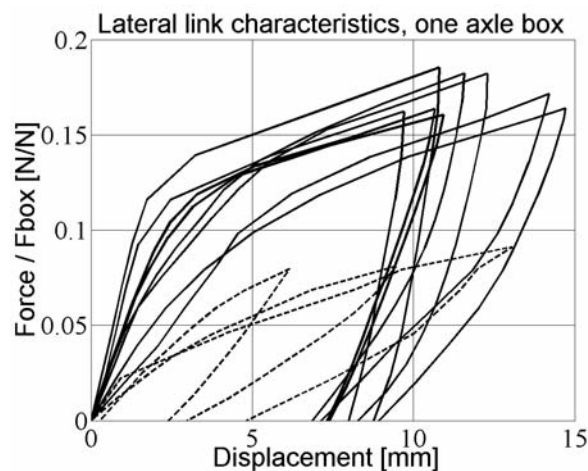


Figure 4: *Stationary measurements on vehicles [21], [23], [48]. Lateral link system characteristics for various single-axle running gear with double links. The lateral forces are normalized with the vertical axle box force.*

Several authors have tried to explain some of the variations through field or laboratory tests and/or with mathematical models [21], [24], [49] and [50]. However, even though the link suspension is simple in its design, as seen in Figure 1, the contacts between the various components create a complex non-linear system. All phenomena that occur in the link mechanism can not be explained by means of the proposed models.

4 LABORATORY TESTS AND THEORETICAL ANALYSIS

To improve the understanding of the link-bearing contact mechanism, laboratory tests are carried out in the present work. An enhanced link system simulation model is proposed to further improve the understanding of the system. The model is verified by comparing results from the laboratory tests. The laboratory tests and the simulation model are described in **Paper A** and summarized here.

A mass is hung from a frame via one link and two end bearings. The upper end bearing is connected to the frame and the lower to the mass. A hydraulic cylinder applies a lateral harmonic motion on the lower end bearing and the force-displacement characteristics are measured. Loading mass, amplitude and frequency are varied during the test according to the following:

- Mass: 660, 1380, 2200 kg (approximately 6 - 17.5 tonnes axle load).
- Frequency: 0.1, 1.0, 2.0, 3.0, 4.0, 5.0 Hz.
- Amplitude: 1, 2, 5, 8, 10 mm (zero to peak).

New components as well as components worn in service are tested.

In Figure 5 some results from the laboratory tests are shown. Figure 5a) shows the load dependence. The lateral force is normalized with the vertical load. We observe that the energy dissipation is approximately proportional to the load. Three sections in the characteristics are identified:

- in section s_1 there is rolling contact between link and end bearings;
- in section s_2 there is sliding contact, the break-out forces due to friction are reached;
- in section s_3 there is a transition zone.

The transition zone may be due to different reasons, such as different conditions for the lower and upper contacts regarding friction, geometry and flexibility. Also other effects may influence the transition zone.

In section s_1 it is observed that the tangential stiffness is *not* proportional to the normal load due to flexibility in link, contact surfaces, end bearings etc.

Dependency of frequency is shown in Figure 5b). In the normal operation frequency range for freight wagons (1 - 3 Hz) there is no significant frequency dependence. However, for the excitation frequency of only 0.1 Hz the amount of hysteresis is lower, as measured in the test rig.

*Modelling and Laboratory Investigations on Freight Wagon Link Suspensions
with respect to Vehicle-Track Dynamic Interaction*

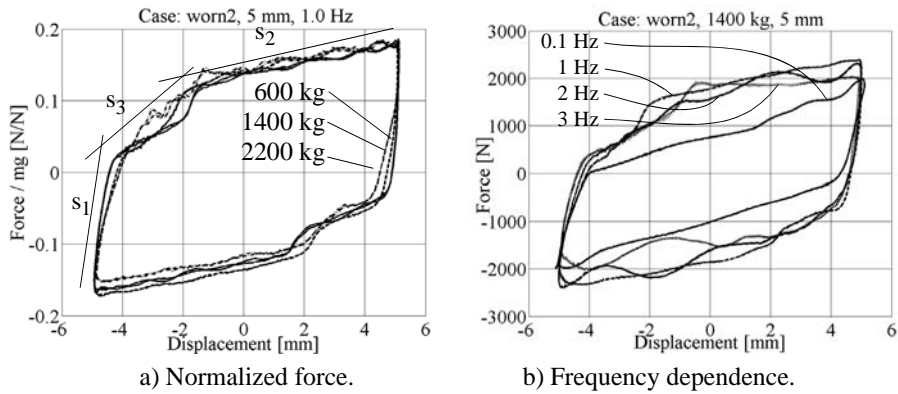


Figure 5: *Laboratory tests on lateral single-link characteristics.*

Scatter in the results from tests on six different links worn in service is shown in Figure 6a). As seen there are significant variations in characteristics.

When we compare tests on new components and components worn in service, the characteristics differ even more as seen in Figure 6b). It appears that the energy dissipation in the hysteresis loop drops dramatically after a few hours of testing.

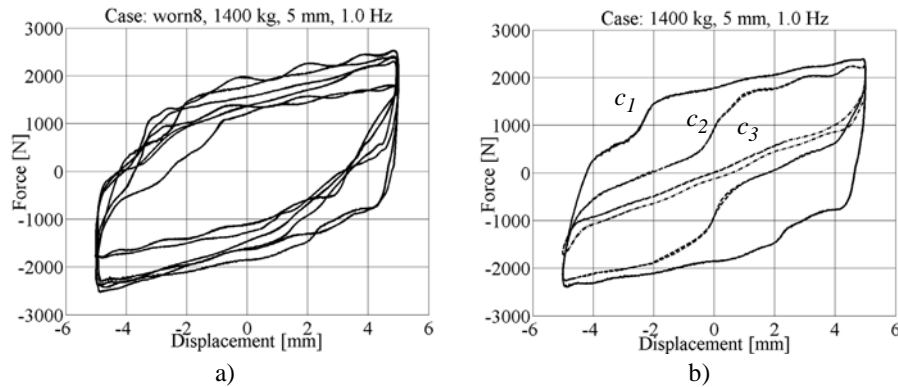


Figure 6: *Laboratory tests on lateral single-link characteristics.*

a) *Scatter between six different links worn in service.*

b) *Development of hysteresis and energy dissipation*

c₁ = Link worn in service

c₂ = New link

c₃ = New link after 220 hours testing.

It is found that real links and end bearings (both new and worn) may have contact radii that differ considerably from the nominal measures specified in the present standards. See further **Paper A**. Most results from the laboratory test are explained by the link

system simulation model. To fully explain the high initial rolling stiffness in section s_1 that occurs in many cases, it is proposed that the elastic deformations in the contact surfaces are taken into consideration. Simulation of load dependence is shown in Figure 7. The lateral forces are normalized with the load. Principally the load dependence is similar to the test results; cf. Figure 5a).

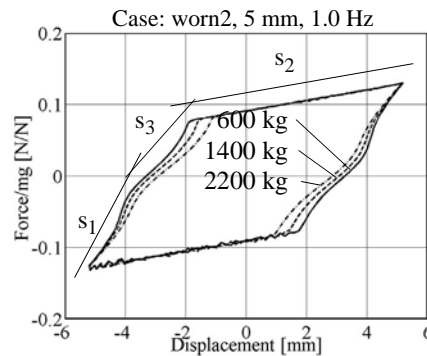


Figure 7: Simulation of lateral single-link system characteristics. Load dependence. Normalized force.

5 IMPROVED RIDE QUALITIES

As seen in Section 4 the various stiffnesses and hysteresis loops have considerable variation and may have strong influence on the ride qualities of vehicles. Means of improving and securing ride qualities are therefore of interest. One way may be to introduce supplementary friction or hydraulic dampers on standard freight wagons.

A tentative simulation study on the possibility to improve ride qualities of freight wagons with link suspension is presented in **Paper B** and summarized here.

As a basis multibody dynamic simulation models of freight wagons with UIC standardized running gear as well as novel designs, are developed and verified with on-track tests [22], [24], [29], [43] and [51]. In the present work a parametric study on the link-suspension bogie is performed by means of the multibody simulation system GENSYS [52]. The effect of supplementary friction and hydraulic damping is investigated under various running conditions: speed, loading, tangent and curved track, wheel-rail contact geometry (expressed as the so-called equivalent conicity [53]), track gauge and track irregularities.

To achieve good ride qualities under all conditions at speeds above 130 á 140 km/h a combination of supplementary hydraulic dampers is proposed. Also friction dampers can be considered. A full damper configuration is shown in Figure 8. To improve ride qualities at lower speeds it may *not* be necessary to use a complete set of supplementary dampers. Also at higher speeds it might be possible to run with a less number of supplementary dampers, depending on the wagon type and loading.

*Modelling and Laboratory Investigations on Freight Wagon Link Suspensions
with respect to Vehicle-Track Dynamic Interaction*

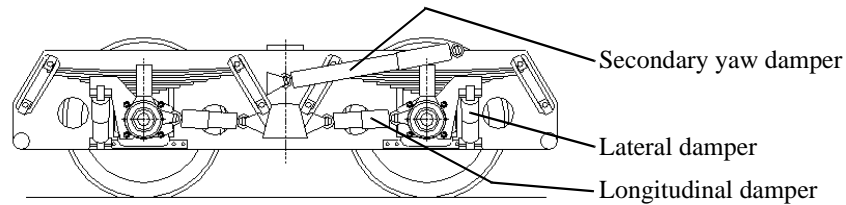


Figure 8: *Improved UIC link suspension bogie. Full damper configuration.*

An example of lateral track shift forces (ΣY) [54] and lateral ride index for freight wagons (WzG) [55] are shown in Figure 9. Results for a standard UIC link bogie as well as for an improved UIC bogie with full damper configuration. A common type of dynamic instability for freight wagons with link suspensions is a low-frequency instability where the carbody yawing interacts with the sinusoidal lateral motions of the wheelsets. The frequency of these lateral motions are usually in the order of 1.5 - 2 Hz. This is the reason for the quite high ride index (around 3.5) of the standard bogie, although the ride qualities are compatible with the previous quite liberal limit value of 4.25. According to the present simulations the improved bogie would have ride indexes of typically 2 - 2.5. This is a substantial difference; if measured in r.m.s. accelerations the standard UIC design exhibits 3 - 7 times higher amplitudes of motion.

Thus for the link suspension bogie considerable improvements can be achieved for ride comfort and track forces on tangent track as well as in curves. It is also possible by supplementary means to achieve similar improvements for two-axled wagons with link suspension [51].

Section 5 - Improved Ride Qualities

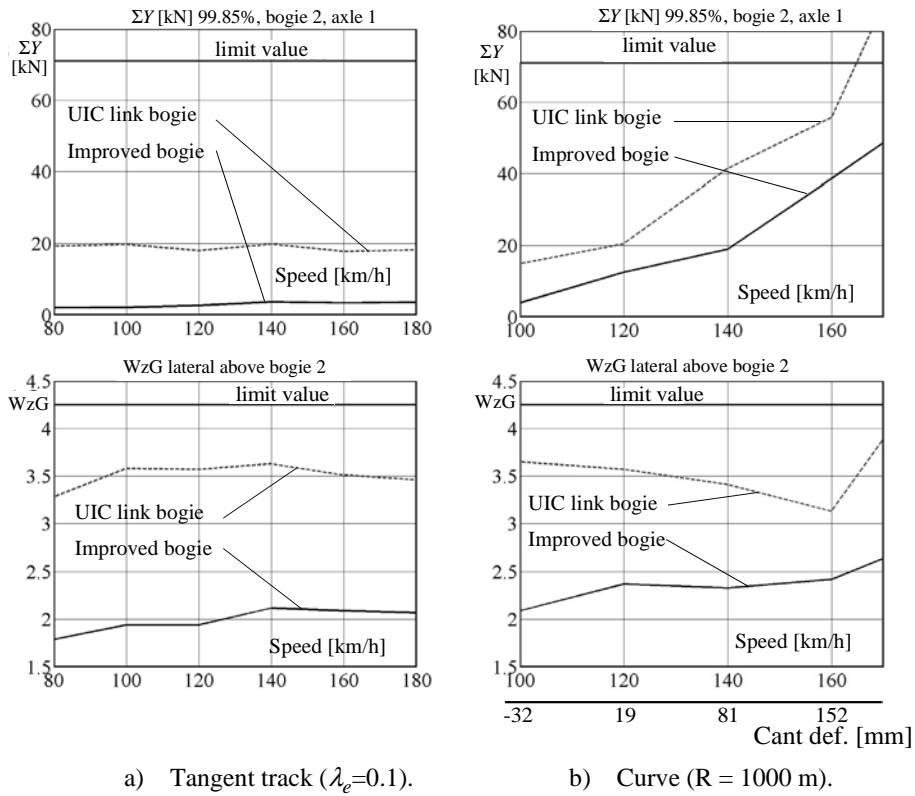


Figure 9: Simulations of lateral track shift force (ΣY) and ride index (WzG). Loaded wagon on tangent and curved track. Full damper configuration according to Figure 8.
a) Tangent track; equivalent conicity $\lambda_e=0.1$.
b) Curved track; curve radius $R=1000$ m.

6 CONCLUSIONS AND FURTHER WORK

Several features and phenomena of lateral link suspension characteristics have been studied in laboratory tests, see Paper A. Some of them are well known from earlier investigations, while others appear to be fairly unknown, or at least not made public. By the development of a simulation model of the link suspension system - as well as of the test rig - it has been possible to study and explain most of the phenomena found in the tests.

The energy dissipation in the hysteresis loop as well as the stiffnesses at sliding contact are approximately proportional to the applied vertical load.

The actual contact geometry of the links and end bearings has a significant influence on the characteristics. By wear in ordinary service the contact geometry changes considerably, thus causing the characteristics to change. Normally the initial stiffness (before the friction break-out force is reached) increases by wear. A low initial stiffness in combination with a high friction in the contacts, may cause a thin hysteresis loop, i.e. a low energy dissipation and damping. Also, the liberal tolerances being allowed contribute to the uncertainty of the contact geometries.

Further, it seems that elastic deformations in the contact surfaces have considerable effects on the suspension characteristics, in particular on the initial rolling stiffness. Also, flexibilities in links and end bearings influence the characteristics - not to forget flexibilities of the parts where the end bearings are attached, i.e. leaf springs, brackets etc.

It is observed that new links after a short period of dynamic testing can exhibit a very low amount of energy dissipation. Indications of this phenomenon are found also in stationary measurements on wagons. However, just a small number of slightly worn components on wagons have been studied so far. More force-displacement measurements on wagons are needed, encompassing suspension components of different maintenance status, i.e. new, slightly worn and worn components.

No significant frequency dependence is found in the normal operation frequency range for freight wagons (1-3 Hz). However, for an excitation frequency of 0.1 Hz the amount of hysteresis and energy dissipation is lower, as measured in the test rig. Whether this phenomenon is restricted to the test rig only, or is typical also for vehicles in operation, has not yet been determined. Further research is needed in this area.

In summary, it appears that the link suspension characteristics are very sensitive to several factors being hard to control in the real world of freight wagon operations. The various stiffnesses and hysteresis loops have a considerable variation and may have a strong influence on the ride qualities of vehicles. As long as the characteristics can not be controlled within closer limits than found in this study, there is a strong need for sensitivity analysis to be made, both in predictive multibody simulations of vehicle dynamics, as well as in verification and acceptance tests.

Supplementary means - for example friction and hydraulic dampers - may be needed as a complement on standard freight wagons, in order to improve and secure ride qualities.

The tentative study of vehicle dynamics, as presented in Paper B, indicate that substantial improvements of the lateral running behaviour of wagons with link

Section 6 - Conclusions and Further Work

suspension bogies can be achieved by using a proper combination of supplementary hydraulic dampers. Speeds up to 160 km/h could be realistic. However, at this point it must be pointed out that all effects of variations in the link suspension characteristics are not considered.

Further research on freight wagon running gear should be focusing on the following topics:

- Any frequency dependency in the link suspension characteristics. Further development of the dynamic link simulation model and verification with respect to these dynamic phenomena.
- Variations in link suspension characteristics. Investigations based on an extended number of stationary measurements on wagons. Accuracy and relevance in the method currently used for measurement must be considered. Longitudinal suspension characteristics should be included.
- The influence of the variation in suspension characteristics on vehicle dynamics.
- Improvements of the dynamics of standard UIC running gear. Vertical dynamics should be included. Comparison of simulations with on-track measurements.
- The effect of various ride qualities, freight wagon characteristics and axle load on track deterioration.

REFERENCES

- [1] **UIC:** *UIC Leaflet 510-1 – Wagons – Running gear – Normalization*, UIC, 9th edition, Paris, 1995.
- [2] **UIC:** *UIC Leaflet 517 – Wagons – Suspension gear – Standardization*, UIC, 6th edition, Paris, 1985.
- [3] **Hawthorne, V. T.:** *Recent improvements to three-piece trucks*, Proceedings of the 1996 ASME/IEEE joint railroad conference, 1996, p 151-161.
- [4] **Scales, B. T.:** *Review of contemporary freight car bogie design*, IMechE seminar on Railway Rolling Stock, 1996, p 97-110.
- [5] **Bullock, R. L.:** *The development and service results of a cross braced radial freight car truck*, Proceedings of the economics and performance of freight car trucks, 1983, Montreal, Canada, p 59-68.
- [6] **Hawthorne, T. V., Sellberg, P. R. and Wronkiewicz, D. R.:** *Effect of maintenance practices upon performance of freight car railroad trucks - Progress report*, Technical paper presented at the 1990 ASME/IEEE joint railroad conference, 1990, p 1-12.
- [7] **Khatchadourian, V.:** *Comparative performance of new generation freight car trucks*, Proceedings of the economics and performance of freight car trucks, 1983, Montreal, Canada, p 179-186.
- [8] **Koffman, J. L.:** *Die Rahmenverschiebung der dreiteiligen Drehgestelle der Bauart Diamond*, ZEV-Glasers Annalen 98, 1974, p 56-60.
- [9] **List, H. A. and Bailey, E. C.:** *Development of a retrofit steering assembly for standard AAA freight car trucks*, Proceedings of the economics and performance of freight car trucks, 1983, Montreal, Canada, p 69-76.
- [10] **McLean, L. A.:** *Second generation freight car trucks - Penecea or Vexation*, Proceedings of the economics and performance of freight car trucks, 1983, Montreal, Canada, p 7-10.
- [11] **McKeown, F., Pitchford, T., Steffen, J. J. and Wronkiewicz, R.:** *High capacity integrated truck*, Proceedings of the 2001 ASME/IEEE joint railroad conference, 2001, p 193-199.
- [12] **Mulder, J. M. and Tournay, H. M.:** *Spoornet's experience refines steering bogies*, Railway Gazette International, May, 1996, p 301-304.
- [13] **Pollard, M. G.:** *The development of cross-braced freight bogies*, Rail International, 1979, p 736-758.

Section 6 - Conclusions and Further Work

- [14] **Scales, B. T.:** *Scales-Devine radial bogie: a solution to wheel/rail interaction*, Rail Engineering International, 1979, p 43-44.
- [15] **Scheffel, H.:** *Die Konstruktion der Kreuzanker-Drehgestelle der Südafrikanischen Eisenbahnen*, ZEV-Glasers Annalen 110, 1986, p 203-208.
- [16] **Smith, R. E.:** *The theory and performance of frame-braced freight trucks*, Proceedings of the economics and performance of freight car trucks, 1983, Montreal, Canada, p 111-117.
- [17] **Jönsson, P.-A.:** *Freight wagon running gear – a review*, TRITA – FKT Report 2002:35, KTH Railway Technology, Stockholm, 2002.
- [18] **Hecht, M.:** *European freight vehicle running gear: today's position and future demands*, Proc. of the Inst. of Mech. Engrs., Part F, Journal of Rail and Rapid Transit, 2001, Vol 215, p 1-11.
- [19] **Madeyski, T.:** *Laufverkskonstruktion und Erhöhung der Radsatzlasten im Güterverkehr*, ZEV-Glasers Annalen 107, 1983, p 139-147.
- [20] **Müller, L. and Niermeyer, W.:** *Weiterentwickelte Güterwagen-Drehgestelle der Deutschen Bundesbahn für 22.5 t Radsatzlast - wieder nach dem Lenkachsprinzip*, ZEV-Glasers Annalen 111, 1987, p 188-196.
- [21] **Stichel, S.:** *On freight wagon dynamics and track deterioration*. Journal of Rail and Rapid Transit, Proc. of IMechE, Part F, Vol. 213, No. F4, London, 1999, p 243-254.
- [22] **Stichel, S.:** *Running behaviour of railway freight wagons with link bogies. A parametric study*, TRITA – FKT Report 1999:12, KTH Railway Technology, Stockholm, 1999.
- [23] **Axelsson, J. and Nellgran, Å.:** *Lateral and longitudinal stiffness of UIC double-link primary suspension* (in Swedish: Lateral och longitudinal styvhet för primärfjädring med UIC dubbellänk). Laboratorierapport 8323-9g, SJ, Stockholm, 1982.
- [24] **Lange, H.:** *Dynamic analysis of a freight car with standard UIC single-axle running gear*, TRITA – FKT Report 1996:34, KTH Railway Technology, Stockholm, 1996.
- [25] **Specht, W.:** *Neue Erkenntnisse über das Verschleissverhalten von Güterwagendrehgestellen*, ZEV-Glasers Annalen 111, 1987, p 271-280.
- [26] **Madeyski, T.:** *Die Güterwagen-Drehgestelle Y25 und 665*, Eisenbahntechnische Rundschau 27, 1978, p 713-720.

*Modelling and Laboratory Investigations on Freight Wagon Link Suspensions
with respect to Vehicle-Track Dynamic Interaction*

- [27] **Moron, P.:** *A standard UIC bogie for freight wagons - The Y25 bogie, variants and development*, Revue Generale des Chemins de fer, 1971.
- [28] **Nielsen, J.:** *Model of the freight wagon bogie Y25 for dynamic analysis in GENSYS* (in Swedish: Modell av godsvagnsboggi Y25 för gångdynamisk analys i GENSYS), Prosolvia Research & Technology, 1996.
- [29] **Jendel, T.:** *Dynamic analysis of a freight wagon with modified Y25 bogies*, TRITA-FKT Report 1997:48, KTH Railway Technology, Stockholm, 1997.
- [30] **Frederich, F.:** *Erkenntnisse über das Fahrverhalten von Güterwagen-Drehgestellen*, Archiv für Eisenbahntechnik, 1984, p 21-32.
- [31] **Evans, J. R. and Roger, P. J.:** *Validation of Dynamic Simulations of Rail Vehicles with Friction Damped Y25 Bogies*, Proceedings of the 15th IAVSD Symposium, Vol. 29, Vehicle System Dynamics, 1998, p 219-233.
- [32] **Frederich, F.:** *Erkenntnisse über das Fahrverhalten von Güterwagen-Drehgestellen*, Archiv für Eisenbahntechnik, 1984, p 21-32.
- [33] **Hecht, M. and Keudel, J.:** *Close-to-Reality Simulation of the Y25 Bogie by Implementation of Measured Characteristics*, 6th International Conference on Railways Bogies and Running Gear, Budapest, 2004.
- [34] **ABC-NACO Europe:** *Higher axle load and lower track forces? Axle Motion bogie for 25 t axle load*, Pamphlet, 2000.
- [35] **Bohumil, V. and Bohumin, J.:** *Drehgestelle mit erhöhter dynamischer Steifigkeit für grössere Radsatzlasten*, ZEV-Glasers Annalen 125, 2001, p 35-40.
- [36] **Müller, L. and Gebhard, H.:** *Laufwerke für hohe Geschwindigkeiten bei Güterwagen*, Eisenbahntechnische Rundschau 39, 1990, p 661-666.
- [37] **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.
- [38] **ERRI:** *Dynamic behaviour of two-axled wagons with a wheelbase of < 8 m*, Question B12 Report 72, 2001.
- [39] **Etwell, M. W. J.:** *Advances in rail wagon design*, IMechE Part F Journal of Rail and Rapid Transit, 1990, p 45-53.
- [40] **Harding, A.:** *Development of the TF25 "track-friendly" bogie*, IMechE seminar on Railway Rolling Stock, 1998, p 43-53.
- [41] **Smith, B. and Harding, A.:** *Low track force bogie widens options*, Railway Gazette International, 1988, p 589-593.

Section 6 - Conclusions and Further Work

- [42] **Powell Duffryn:** *TF25SA Single Axle Suspension*, Pamphlet, 2001.
- [43] **Thomas, D.:** *Development and Verification of a Multibody Dynamic Simulation Model for a Freight Wagon with Powell Duffryn TF25SA Running Gear*, TRITA AVE 2003:18, KTH Railway Technology, Stockholm, 2003.
- [44] **Meridian Rail Europe:** *Track friendly freight bogies for 25 t axle load*, UIC seminar, Frankfurt, 2002.
- [45] **Auroy, M.:** *SNCF to launch Europe's fastest freight trains*, Railway Gazette International, 1987, p 98-99.
- [46] **Dancoisine, J. M.:** *Introduction of 160 km/h freight trains*, Rail International, 1988, p 29-34.
- [47] **Müller, L.:** *Konzepte für Güterwagenlaufwerke für Geschwindigkeiten über 120 km/h*, Eisenbahntechnische Rundschau 37, 1988, p 799-802.
- [48] **Wrang, M.:** *Litt. Laagr-w, force/displacement measurements (in Swedish: Litt. Laagr-w kraft/förskjutnings-mätningar)*, TrainTech Laboratorierapport 0147-62g, 2001.
- [49] **Pascal, J. P.:** *Oscillations and chaotic behaviour of unstable railway wagons over large distances*, Chaos, Solutions & Fractals 5(9), 1995, p 1725-1753.
- [50] **Piotrowski, J.:** *Model of the UIC link suspension for freight wagons*, Archive of Applied Mechanics 73, 2003, p 517-532.
- [51] **Stichel, S.:** *Running behaviour of railway freight wagons with single-axle running gear*. TRITA-FKT Report 1998:40, KTH Railway Technology, Stockholm, 1998.
- [52] **Persson, I.:** *Using GENSYS.0403*, ISBN 91-631-3110-2, DEsolver, Östersund, 2004.
- [53] **Andersson, E., Berg, M. and Stichel, S.:** *Rail Vehicle Dynamics*, KTH Railway Technology, Stockholm, 2004.
- [54] **UIC:** *UIC Leaflet 518 - Test and acceptance of railway vehicles from the point of view of dynamic behaviour, safety, track fatigue and quality of ride*. UIC, Paris, 2003.
- [55] **ORE C116/Rp 8:** *Method for assessing Riding Qualities in Vehicles*, Utrecht, Netherlands, 1977.