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Life Cycle Costs of Freight Wagons with Composite Brake Blocks and Disc Brakes

Edited by

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1 Assignment and Methodology

The Institute for Transport Planning and Systems (IVT) of ETH Zurich has been commissioned by the Swiss Federal Office for the Environment (BAFU), to conduct a study and a presentation on life cycle costs for railway freight wagons with composite brake blocks and disc brakes. The aim of this assignment was to investigate the current state of knowledge about life cycle costs for railway freight cars. Basic focus was the differentiation according to the types of brakes: cast iron-, K-, LL-blocks and disc brakes. The cost of procurement, wear of wheel and brake lining and maintenance were to be distinguished.

Mr Fredy Fischer was responsible for the project on the client side. He was assisted by Mr Christoph Wenger.
Originally, the project responsibility on side of the contractor was planned to be at IVT, which subcontracted the Department of Rail Vehicles of the TU Berlin (FG Schienenfahrzeuge). Due to short-term changes in personnel at the IVT, the Department of Rail Vehicles finally worked on the whole assignment. The work was executed by Prof. Dr.-Ing. Markus Hecht (head of chair) and Mr. Daniel Jobstfinke M.Sc. (research assistant). The IVT, namely Prof. Dr. Ulrich Weidmann, has proofread this report and represents its content.

The information on LCC compiled in this report were largely collected through a literature review in scientific publications and journals. Furthermore, LCC have been calculated using a program of the railway industry. This program uses cost rates of the various actors (stakeholders) of the rail freight sector that were determined in real operation. Thereby, both different types of defined scenarios and average cost rates of a various scenarios of operation and various stakeholders have been considered.

In accordance with the offer, the determined LCC are indicated in Swiss francs per vehicle kilometer. Since the cost rates in the literature and in the used program are typically reported in Euros, they were converted at an exchange rate of 1,0455 CHF/EUR. However, this is a pure currency translation. Different cost levels, e.g. for wages, are not considered. In order to avoid confusion, the present English version of the study uses the same decimal separator (,) and thousands separator (.) as in the German version.

2 Summary

All reviewed sources show that the use of composite brake blocks leads to an increased service life of the brake blocks in comparison to cast iron brake blocks. However, there is also a reduction in the service life of the wheels, so that the total life cycle costs (LCC) of a wagon with composite brake blocks rise compared to a wagon with cast iron blocks.
The exact extent of this increase depends largely on the specific type of operation and conditions of that freight wagon. Even various freight wagons with cast iron brake blocks show different wear rates (40 % to 60 % deviation), which affect up to 9 % variation in the operating costs of the running gear.
A “quasi ss-traffic” wagon[1] that runs in a train mixed with s-traffic wagons[2], causes an approximately 1,5-fold wear on brake components with both composite and cast iron blocks. This should be the upper limit of the additional wear of ss-traffic wagons with kink valves in mixed trains.

The data determined in this study for additional operating costs for brakes with composite brake blocks basically ranges over two different cost areas. One cost range is from about 0,017 CHF/km to 0,024 CHF/km. The other cost range extends from just below 0 CHF/km to about 0,010 CHF/km. The disc brake is also located in the latter cost range. With only one exception, the calculations carried out show that the disc brake is more economical than all investigated composite brake blocks from about 55.000 km annual running distance. According to the calculations, the disc brake is even more economical than the cast iron blocks from 135.000 km annual running distance. However, it is to be noted that only one source is used for the data of the disc brake.

Measures for the reduction of brake-related LCC of freight wagons are increased use of electro-dynamic brakes (while increasing the permissible longitudinal compressive forces, and/or use of automatic couplers), the widespread introduction of ETCS Level 2 and real-time intelligent dispositioning systems. In addition, the disadvantage of high investment costs of the disc brake could be mitigated by interest-free loans.

[1] Wagon, which corresponds in its brake design to a wagon that can run with 120 km/h in the loaded state (ss-traffic), but is not equipped with a kink valve.
[2] Wagons, which can run with 100 km/h in the loaded state (s-traffic).

3 Introduction

The current state of knowledge on life cycle costs (LCC) of railway wagons with focus on different types of brakes is displayed in the present study. The focus of the investigation lies on the additional operating costs for block brakes with composite blocks and disc brakes compared to block brakes with cast iron blocks. Various scientific publications and journals are evaluated. Furthermore, operating costs of the block brake with cast iron blocks are shown based on existing calculation models. In addition, the influence of different application scenarios of the freight wagon in terms of annual running distance, train composition (block train vs. mixed train), the maximum speed of the wagon (s and ss-traffic) and operational area are considered.

Firstly, section 4 shows technical basics and terms of the braking system and other components of the wagon that are relevant for the operating costs of the wagon. Section 5 presents the used data sources and for each source both the boundary conditions of the data collection and the specific results. Section 6 then shows the results of this study. An examination of the LCC for the use of cast iron blocks and the influence of boundary parameters on the LCC is followed by a clear presentation of the evaluated additional costs of the use of composite brake blocks and disc brakes compared to cast iron. Finally, a brief overview of ways to reduce operating costs caused by the brake system is given.

4 Technical Basics and Terms

Every European railway freight wagon is equipped with the automatic air brake. In this braking system, the medium “compressed air” is both signal transmission medium and energy medium.
Reductions of the pressure level in the train line are transferred to increases of the pressure in the brake cylinders of the wagons by the wagon’s control valves. A force is generated from the pressure in the brake cylinders. This force acts on the friction elements by means of levers and linkages. Friction elements are the brake blocks and the wheels if the block brake is standardly used on freight wagons. The brake blocks are pressed onto the running surface of the wheels by the force from the brake lever. The resulting frictional force, which depends on the friction coefficient between the brake block and the wheel in addition to the pressing force, leads to a deceleration of the wagon. During braking, wear occurs on the two friction partners brake block and wheel.

In case of the disc brake, which is (still) rarely used in the freight wagon sector, the force of the brake lever is transmitted on brake pads. These brake pads are thereby pressed onto brake discs. The resulting frictional force between brake pad and brake disc leads to a deceleration of the wagon. During braking, wear occurs on the two friction partners brake pad and brake disc. In comparison to block brakes, only minimal wheel wear occurs due to slip between wheel and rail. In addition, the brake pads and discs usually last longer than brake blocks and wheels. However, a disadvantage of the disc brake is their greater weight, their higher rotating masses and their higher procurement costs.

Different friction materials are used for the brake blocks. Traditionally, blocks made of cast iron (CI)[3] are used. These have the disadvantage that they roughen the running surface of the wheels during braking, thus resulting in a permanently higher rolling noise. This effect does not occur with the use of composite brake blocks. Composite brake blocks are made of metallic or organic components, which are either sintered or pressed into form in elastomer compounds. Two different types of composite brake blocks have to be distinguished: The K-blocks (composite block) and the LL-blocks (low noise, low

[3] So called P10-blocks are standardly used. Their alloy contains an amount of 1 % phosphorus next to iron, carbon, and some other elements.

friction block or very low friction block). The K-blocks have a much higher friction coefficient than CI-blocks and are therefore not interchangeable with them. For the use of K-blocks the entire brake system of a wagon has to be adapted. However, the LL block has a similar frictional behavior like the CI-blocks. Therefore, the LL-blocks are interchangeable with the CI-blocks. The exemplary friction coefficient characteristics of the various brake block materials can be found in Figure 1. The allowable tolerance bands of friction can be obtained from the UIC leaflets.

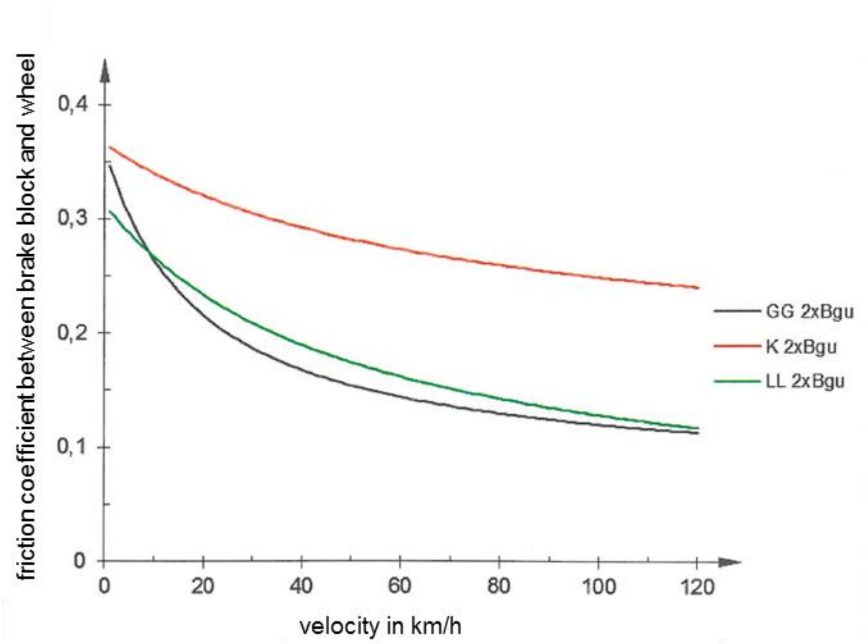

Figure 1: Exemplary friction coefficient characteristics of various brake block materials. Altered from [1]

It is necessary to distinguish between different wear mechanisms of the wheel caused by the brake blocks. Firstly, there is a (general) removal of material from the running surface of the wheels. Wear limit sizes of the wheel are relevant in this case. Secondly, this removal of material may lead to a change of the wheel's running surface profile. The wheel's running surface is not cylindrical but has a non-linear profile, which is relevant for the track guiding of vehicles. The running behavior of a vehicle with specific wheel profiles on a track with specific rail profiles can be expressed by the linearized replacement size of the equivalent conicity (EC).

The replacement model is a double cone, which runs on round rails. If this double cone has the same hunting oscillation like the real vehicle on the real track, the conicity of the double cone equates to the equivalent conicity. This is illustrated in Figure 2.

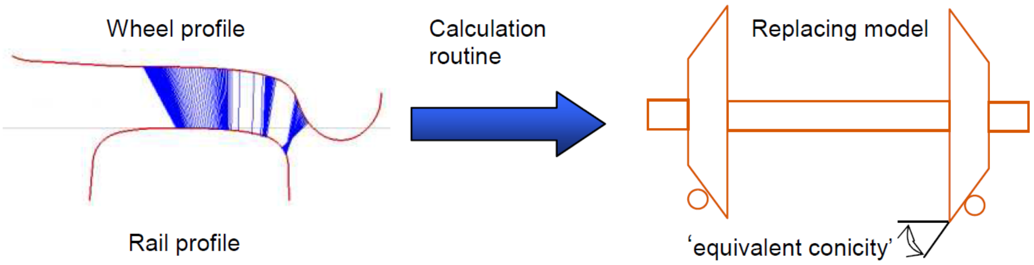

Figure 2: Schematic representation of the determination of the equivalent conicity [5]

A high equivalent conicity has a negative effect on the running stability of railway vehicles. When using CI-blocks, the equivalent conicity increases initially only slightly and remains constant later. However, in particular when using LL-blocks, it comes to a steady growth of the equivalent conicity. [2] The permissible equivalent conicity of a freight wagon is set to 0,4. [3]

In regard to the speed limits of freight wagons it can be distinguished between wagons for the fast traffic (s-traffic) and the very fast traffic (ss-traffic). The wagons in s-traffic can run at speeds of 100 km/h in the laden state. The prerequisite is that they reach at least a braked weight percentage of 65 in the laden state. The wagons in ss-traffic can run at speeds of 120 km/h in the laden state. The prerequisite is that they reach a braked weight percentage of 100 in the laden state for axle loads up to 18 t and a braked weight percentage of 90 from axle loads over 18 t to 20 t.
Wagons which are marked with at least two stars ** have a running gear capable of running at speeds of 120 km/h in the laden state but do not have the braking requirements for ss-traffic conditions.

5 Presentation of Used Sources

As it will be described in detail later in this study, LCC of freight trains depend strongly on the application circumstances. Furthermore, a measurable wear of components relevant to the brake system, especially at wheels, brake blocks and, if applicable, brake discs, is only encountered after an increased running distance. LCC data is primarily obtained from scientific publications in order to apply clearly defined and documented boundary conditions to (long-term) surveys. Data is not obtained from rail freight traffic stakeholder questioning. They are in possession of real cost rates, however, the specific type of operation and conditions of a wagon vary frequently and above all, they are usually not sufficiently documented. Instead, additional data is taken from a simulation software of the railway industry. Average real cost rates of different stakeholders and different boundary conditions / scenarios serve as a data base for this software.
In the following, the sources will be described in detail and the data relevant to this study will be pointed out.

5.1 Project “Dolomite Shuttle”

5.1.1 Boundary Conditions

In 2002 Lloyd’s Register was commissioned to lead a project to test noise-reducing measures for freight trains and their impact on LCC. The project was part of the Noise Innovation Program (Innovatie Programma Geluid, IPG) of the Dutch Ministry of Transport, Public Works and Water Management (Ministerie V&W), which analyzed rail as well as road traffic. Further major participants were the railway operator Railion Nederland and railway network infrastructure operator ProRail. Unless specially marked, the following information was obtained from [4].
In the context of the project, a freight train was partly retrofitted with the K-block type Cosid C810 and examined over several years until 2007. In order to facilitate a comparison some wagons remained in the original state with cast iron blocks. The train ran in a fixed constellation of 29 wagons of the type Tapps between Hermalle in Belgium and Veendam in the Netherlands three times a week. The wagon’s brakes were designed to a maximum speed of 100 km/h in the laden state (s-traffic). The freight consisted of the

mineral dolomite and the annual running distance was 90.000 km. The thickness of the brake blocks as well as the wheel profiles were recorded every three months.

5.1.2 Project Results

Unless specially marked, the following information was obtained from [4]. During the testing wear of the K-blocks of 17 mm/100.000 km and of the CI-blocks of 52 mm/100.000 km was measured. As the wear of the K-blocks was asymmetric (more material was removed from the upper than from the lower end of the block; the carrier plate of the block was consequently no longer concentric with the wheel), the theoretical service life reduced from 230.000 km to an actual service life of only 130.000 km.
The wheels equipped with CI-blocks had a wear in diameter of 1 mm/100.000 km, whereas the wheels equipped with K-blocks wore with 3,2 mm/100.000. Wheels with reduced flange thickness were used in advance for the wagons with K-blocks.[4]

Figure 3: Plastic deformation of material due to rolling mechanisms in the area of the wheel's bevel [4]

The average running distance until re-profiling of the CI-braked wheels was 350.000 km and 13 mm of the diameter were removed. Regarding the K-braked wheels, the average running distance until re-profiling was 230.000 km and on average 9 mm of the diameter were removed. At the K-braked wheels 100 % of all incidents the reason for re-profiling was a plastic deformation of material due to rolling mechanisms in the area of the wheel's

[4] Experience shows that a slow increase in the flange thickness appears in operation with composite brake blocks due to wear processes. Through a pre-reduced flange thickness it is less likely that the limiting dimension of the flange thickness is exceeded in operation between re-profiling of the wheels.

bevel. This phenomenon is shown in Figure 3. Other defects like wheel flats, profile wear or damages on the running surface did not occur.
The additional operation costs for a four-axle wagon with K-blocks in comparison to wagons with CI-blocks at an allowed equivalent conicity of 0,6 are stated to be **0,0050 €/km or 0,0052 CHF/km**. [5]

5.2 Project "Whispering Train"

5.2.1 Boundary Conditions

In connection to the project "Dolomite Shuttle" the Dutch Ministry of Transport, Public Works and Water Management, the railway network infrastructure operator ProRail as well as the railway operator DB Schenker Nederland decided to conduct tests in the same manner for LL-blocks as part of the Noise Innovation Programme (IPG). These tests comprised of equipping wagons with various LL-blocks by various companies beginning in the year of 2005 and conducting regular tests during normal operation services between 2006 and 2009. In the beginning these tests were conducted monthly and then later, due to positive results, every four months. Data relevant to LCC was collected at only some wagons, whereas data critical to safety was collected at every wagon. All sub-projects combined formed the main project "Whispering Train", which was led by Lloyd's Register Rail Europe with the objective, amongst others, to determine the LCC of LL-blocks. Unless specially marked, the following information was obtained from [5].The project consisted of the following sub-projects:

<u>Cobelfret Car Carrying Wagons</u>

Commissioned by ProRail, the wagon owner Cobelfret Rail equipped 72 car carrying wagons of the types Laeks and Laaers with LL-blocks. Some wagons of each type were equipped with blocks of the type CoFren C952 and C952-1 respectively [5] and some wagons of type Laeks with the block type Jurid J777. 15 wagons of both types continued operation with CI-blocks to facilitate a comparison. The wagons were operated randomly

[5] The block type C 952 is not permitted today any more. Consequently, the manufacturer CoFren developed the block C952-1.

between Dillingen in Germany, Genk in Belgium and the harbor Flushing in the Netherlands. Furthermore, there were some occasional runs to Kiel in Germany, Zeebrugge in Belgium and to some places in Italy. The wagon’s brakes were designed to a maximum speed of 100 km/h in the laden state (s-traffic). The freight consisted of automobiles, the annual running distance was 50.000 km and an average total running distance of 130.000 km was examined.

DB Schenker Container Wagons

Commissioned by DB Schenker Nederland, the wagon owner Ahaus-Alstätter Eisenbahn (AAE) equipped nine container wagons of the type Sgns with LL-blocks of the type CoFren C952 and C952-1, respectively, and of the type Jurid J777. Eight wagons continued operation with CI-blocks to facilitate a comparison.

The wagons ran daily between Stein in the Netherlands and the harbor of Rotterdam. The wagons were set in mixed freight trains and were spread randomly within them.

The wagon’s brakes were designed to a maximum speed of 100 km/h in the laden state (s-traffic). The freight consisted of containers, the annual running distance was 60.000 km and an average total running distance of 175.000 km was examined.

ACTS Container Wagons

Commissioned by ProRail, the wagon owner ACTS equipped 16 container wagons of the type Sgns with LL-blocks of the type Becorit IB116*. Five wagons continued operation with CI-blocks to facilitate a comparison. The wagons ran daily between either Veendem or Leeuwarden in the Netherlands and the harbor of Rotterdam. The wagons were set in mixed freight trains and were spread randomly within them.

The wagon’s brakes were designed to a maximum speed of 100 km/h in the laden state (s-traffic). The freight consisted of containers, the annual running distance was 100.000 km and an average total running distance of 300.000 km was examined.

VTG Tank Wagons

Commissioned by ProRail, the wagon owner VTG equipped ten tank wagons of the type Zas with LL-blocks of the type CoFren C952 and of the type Jurid J777. Four wagons continued operating with cast iron blocks to facilitate a comparison. The wagons ran between Sittard in the Netherlands and the harbor of Rotterdam. There is no information about the train constellation.

The wagon’s brakes were designed to a maximum speed of 100 km/h in the laden state (s-traffic). The freight consisted of chemical products, the annual running distance was 25.000 km and an average total running distance of 75.000 km was examined

5.2.2 Project Results

All information, if not separately marked, was obtained from [5]. In all applications it was found that the wear of LL-blocks was lower than the wear of CI-blocks. Consequently, a longer service life of LL-blocks was detected. However, large differences in the length of service life were found between the different applications as well as between the different LL-block types. Furthermore, all applications showed an increased wear of LL-braked wheels compared to CI-braked wheels. Large differences in wear with respect to different applications and different LL-block type were found, too.

The most important factor in the decrease in service life was the increase of the equivalent conicity. Since there were no international acknowledged limits for the equivalent conicity at that time, the LCC were examined for the three scenarios of an approved equivalent conicity of 0,23; 0,40 and 0,60.

Besides this wear mechanism, an increase of the flange thickness and plastic deformation of material due to rolling mechanisms occurred more often at LL-braked wheels than at CI-braked wheels. Wheel flats and out of roundness occurred more rarely though.

The highest increase in LCC was found at the block type J777, which is not permitted today anymore. The lowest increase was found at the block type IB116*. The LCC of the block type C952 was between them, but this block type is not permitted today anymore either. About its subsequent brake block, C952-1, however, enough information for evaluation could not be collected. The average data is shown in Table 1.

Table 1: Averaged additional LCC for a four-axle wagon in the project "Whispering Train". EC = equivalent conicity. Data from [5]

Block type	Additional LCC per km			
	Min. (EC = 0,6)		Max. (EC = 0,23)	
	in EUR	in CHF	in EUR	in CHF
J777	0,010	0,0105	0,053	0,0554
C952	0,003	0,0031	0,031	0,0324
IB116*	0,004	0,0042	0,017	0,0178

The additional LCC of wagon compared to a wagon with CI-blocks over the service life at a permissible equivalent conicity of 0,6 are shown in Figure 4. The wagon's individual annual running distance is taken into account in this representation. The mean additional LCC per kilometer at a considered service life of 20 years[6] can be calculated from this. These values are shown in Table 2. In particular, the block type C952 shows a wide disparity in the additional cost per kilometer in various applications.

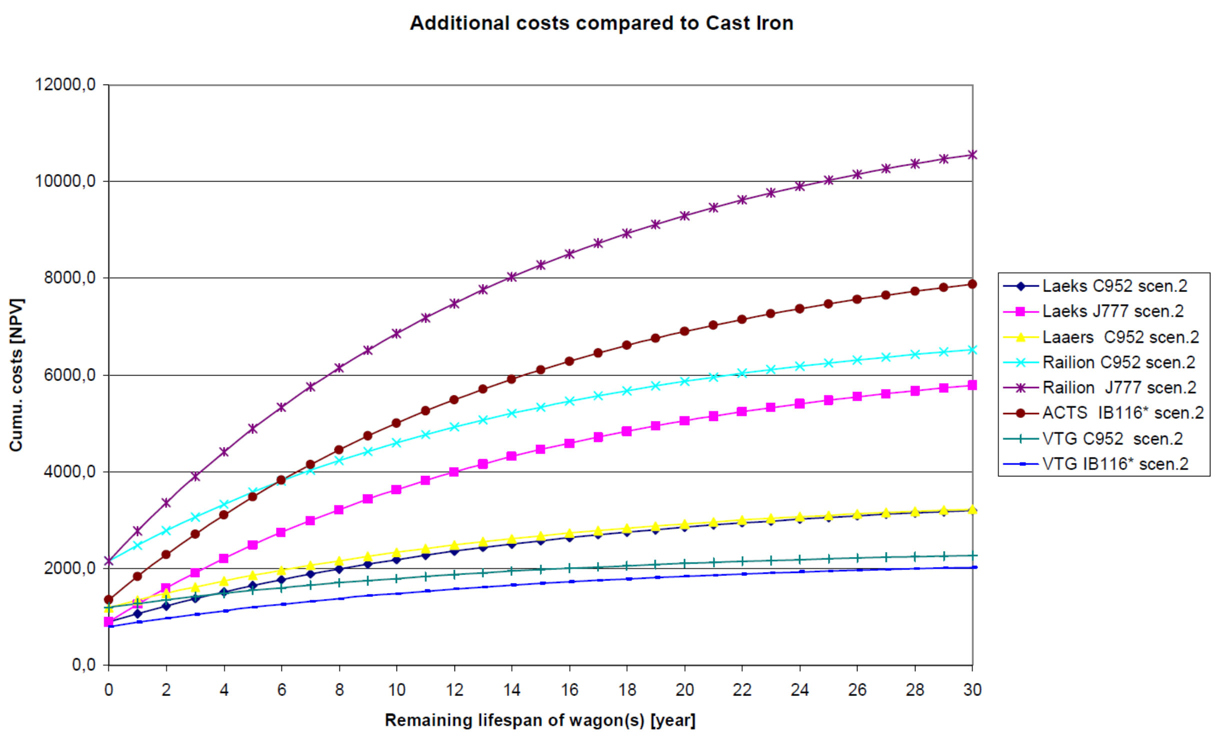

Figure 4: Additional LCC in EUR of wagons in the project "Whispering Train" compared to wagons with CI-blocks over the service life at a permissible equivalent conicity of 0,6 [5]

[6] 20 years have been selected at this point, because the TIS LCC tool (presented in the following) also considers a service life of 20 years.

While it is explicitly stated that the wagons were randomly distributed in mixed freight trains in the case of DB Schenker wagons with C952-blocks, there are no further details for the Cobelfret and VTG wagons. Due to a figure in [5] however, it can be assumed that the Cobelfret cars ran at least partially in unit trains. Whether this is a valid reason for the relatively low additional LCC cannot be known with certainty.

Table 2: Calculated additional LCC of wagons in the project "Whispering Train" compared to wagons with CI-blocks over 20 years with a permissible equivalent conicity of 0,6. Data from [5]

Sub-project and block type	Additional LCC per km	
	in EUR	in CHF
Cobelfret C952	0,0029	0,0030
DB Schenker C952	0,0049	0,0051
ACTS IB116*	0,0035	0,0037
VTG C952	0,0042	0,0044
VTG IB116*	0,0036	0,0038

5.3 Project "Leiser Rhein / Leiser Güterverkehr"

5.3.1 Boundary Conditions

The German government initiated the pilot and innovation project "Leiser Rhein / Leiser Güterverkehr" ("Quiet freight / Quiet Rhine")[7] in 2008. The project was headed by the former Federal Ministry of Transport, Building and Urban Developing (BMVBS). Further involved were the former Federal Ministries of Environment, Nature Conservation and Nuclear Safety (BMU), of Economics and Technology (BMWi) and Finance (BMF) and the Federal Railway Authority (EBA), the Federal Environment Authority (UBA) and the Federal Network Agency (BNetzA). [6]

About 5000 freight wagons should be retrofitted with K- or LL-blocks and mainly be used on routes through the Rhine Valley. Originally, the trips through the Rhine Valley should be verified both by automatic checking (RFID chips on the wagons and reading stations along the route) as well as by unified wagon lists from the involved railway operators. However, only the latter variant was actually implemented. [6]

[7] The term "Quiet Rhine" seems to be synonymously used with "Quiet Freight" in the final report entitled "Pilot- und Innovationsprogramm 'Leiser Güterverkehr'" [6]. The term "Quiet Rhine" is also widely used in media.

The project should serve as incentive for retrofitting of wagons with noise-reducing brake blocks, as demonstration for the effectiveness of these measures and for the examination of ways of developing a noise-related track access charge system.
A list of all railway operators and wagon owners participating in the project is not known. The actual number of retrofitted wagons, the types of retrofitted wagons, the running distances or details to determine the wear rates and their impact on the costs are not known either. It is only ensured that DB Schenker Rail and the Ahaus-Alstätter Eisenbahn were involved in the project. [7]
[8] shows that the wagons retrofitted with K-blocks comprised both wagons for s- and for ss-traffic, while no wagons for ss-traffic were among the retrofitted ones with LL-blocks.

5.3.2 Project Results

The specification of costs for retrofitting and increased operating costs, which were determined in the project "Quiet Rhine" until 2011 and published in [9], can be found in Table 3. A reference running distance of 30.000 km is mentioned in the source. The same values for the costs can also be found in [8].

Table 3: Additional LCC in the project "Quiet Rhine" compared to cars with CI-blocks. Data from [9]

Costs	LL-block (4 axles)	K-block (4 axles)
Retrofitting costs **Bg** in EUR	1250 - 2030	5650 - 6850
Retrofitting costs **Bgu** in EUR	1500 - 2280	6250 - 7450
Increased operating costs per year in EUR (running distance 30.000 km)	500 - 600	600 - 770

Considering each the average values, **one-time retrofitting and a service life of 20 years** excluding interest effects, additional costs per kilometer according to Table 4 arise.

Table 4: Average additional LCC in the project "Quiet Rhine" compared to wagons with CI-blocks at an observation period of 20 years

Block	Additional LCC per km	
	in EUR	in CHF
LL	0,021	0,022
K	0,034	0,036

Excluding the retrofitting costs from the data in Table 3, the average additional costs per kilometer according to
Table 5 arise.

Table 5: Average additional LCC in the project "Quiet Rhine" compared to wagons with CI-blocks at an observation period of 20 years and excluding the costs of retrofitting

Block	Additional LCC per km	
	in EUR	in CHF
LL	0,018	0,019
K	0,023	0,0240

According to a study by the International Union of Wagon Keepers (UIP) [10] additional costs of **0,0188 EUR/km for the organic LL-block** and **0,0204 EUR/km for the K-block** arise for a four-axle wagon. According to the study, the basic data was obtained from the project "Quiet Rhine" for the period until 2011. A reference figure for the running distance is not specified in both cases. Assuming 30.000 km by analogy with Table 3, additional costs in the amount of 564 EUR for the LL-block and of 612 EUR for the K-block result. These values are within the limits set out in Table 3. However, the retrofitting costs seem to be not taken into account.

5.4 Project "EuropeTrain"

5.4.1 Boundary Conditions

All information, if not separately marked, was obtained from [2]. The project "EuropeTrain" was launched in September of 2009 as part of the approval process of LL-blocks. The aim was, inter alia, to gain experiences on the wear behavior of brake blocks and wheels in operation and to gain understanding about the dynamic effects of the increase in the equivalent conicity. The project was led by the working group B 126.13 E of the UIC and performed, inter alia, in cooperation with the wagon keepers DB Schenker, Société Nationale des Chemins de fer Français (SNCF), AAE, Rail Cargo Austria and Železničná spoločnosť Slovensko (ZSSK) Cargo.

To achieve the aforementioned goals, a test train was compiled as part of the project. It consisted of 32 cars of different types and brake designs and ran more than 200.000 km over the European railway network from December 2010 until September. All the topographical and climatic characteristics of twelve European countries were taken into account.

The focus was on wagons for s-traffic but also four wagons for ss-traffic should be set in train. Within the train, there was a balance between wagons with Bg and Bgu brakes. Some of the cars in each configuration ran with LL-blocks (block types CoFren C952-1 and Becorit IB116*)[8] and another part ran with CI-blocks for purposes of comparison. The state of loading of each wagon was varied between runs. About half of all wagons were laden in each run. The other half was empty. The wagons had a good state of maintenance and were equipped with newly re-profiled wheels with reduced flange thickness.

The train ran under normal operating conditions and not as a test train. On downhill stretches both repeated significant reductions of speed followed by subsequent accelerations up to the maximum speed limit ("Sägezahnbremsungen") as well as keeping a constant velocity ("Regulierbremsungen") were carried out. The block wear was measured every time between two runs at three points of the block. The three values were averaged and then again averaged per wagon. The wheel profiles were recorded with a profile measuring device. The change in the flange height was determined from the measured profiles. This change was evaluated as a measure for the wear of the wheel.

5.4.2 Project Results

5.4.2.1 Wear behavior of blocks and wheels

Following results of the project "EuropeTrain" regarding the wear of brake blocks can be stated:

- *All LL block types have lower wear than cast iron. The sinter block C952-1 has only 20 % of cast iron wear, the organic block IB116* has only 52 % of cast iron wear (when laden).*
- *The block wear varies greatly between runs.*

[8] Furthermore, some cars were equipped with the Becorit IB116* Combi block. This block is a mixture of the IB116* and the CI-block. Results of this block are not explicitly shown in the following.

- *Wear rate and braking energy generally correlate.*

Translated quote from [2]

Section 5.4.2.2 of this report also deals with the issue of the last bullet point. Table 6 shows the average brake block wear rates for the different block types

Table 6: Brake block wear rates in the project "EuropeTrain". Compiled with data from [2]

Block wear rate	Block type					
	CI empty	CI lad.	C952-1 empty	C952-1 lad.	IB116* empty	IB116* lad.
in mm/10.000 km	2,08	7,99	0,78	1,67	1,28	4,00
in % of CI	100	100	37,45	20,88	61,47	50,10

In analogy to the findings regarding the brake block wear, the following results from the project "EuropeTrain" regarding the wheel wear can be stated:

- *The wheel wear varies depending on the brake block type; LL-blocks cause increased wear of the wheels.*
- *The wheel wear varies greatly from run to run. An average high wear was found on the runs to Sweden [...], Italy [...] and Eastern Europe [...]. On the runs to France, there was clearly a relatively low wheels wear*
- *For runs through the Alps and Germany, the results are much more different. A high wheel wear was clearly caused in run 5 (Switzerland), in run 8 (Austria) it was clearly less. In run 2 through Germany (south-west), a higher wheel wear was found than in run 13 (north-east direction).*
- *The wheel wear in runs through Eastern Europe is relatively high in relation to the absorbed braking energy. Currently there is no explanation for it.*
- *The wheel wear in the Austria run is relatively low compared to the block wear and absorbed braking energy. The total amount of energy is similar to the run in Switzerland [...], however, the wheel wear in Austria was much lower than in Switzerland.*
- *The wheel wear depends greatly on the loading state of the wagons.*
- *The wheel wear depends on the wagon type [...].*

Translated quote from [2]

The influence of s- and ss-traffic on the wagons is shown in Section 5.4.2.3. The average wheel wear rates (expressed in differences between the wheel flange height ΔSh) for the different block are shown in Table 7.

Table 7: Wheel wear rates in the project "EuropeTrain". Compiled with data from [2]

Wheel wear rate	Block type					
	CI empty	CI lad.	C952-1 empty	C952-1 lad.	IB116* empty	IB116* lad.
ΔSh in mm/100.000 km	0,7	0,9	0,8	2,2	0,8	1,8
in % of GG	100	100	109	237	109	194

5.4.2.2 Characteristics of brake applications

Parameters of the pneumatic brakes were also measured and recorded at some wagons within the "EuropeTrain" project. This made it possible to determine specific characteristics of the brake applications in the runs. Specifically, these parameters were:

- Number of brake applications per 10.000 km
- Number of brake applications with an average train deceleration of 0,3 m/s² or more per 10.000 km
- Number of brake applications with a duration of 30 seconds or more per 10.000 km
- Energy absorbed in the reference car

While the latter two parameters have a distinct topography influence (long brake applications and high energy input during downhill runs), the first two parameters significantly depend on operational parameters such as braking distance, signal and train protection system, driven speed, disposition etc.

The following results can be stated:

- *In general, the energy input of the runs of the same country is highly reproducible.*
- *The number of brake applications with an average deceleration of more than 0,3 m/s² and the number of brake applications longer than 30 s already distinguish stronger, but normally the trend is similar.*
- *The four runs in France (Belgium, the Netherlands) are similar, as are the two runs in Sweden.*

- *The number of brake applications per 10.000 km varies from 618 to 2553 (factor 4).*
- *The highest proportion of brake applications with an average deceleration of more than 0,3 m/s² was measured in Germany (Germany max. approx. 29 % of all brake applications and Poland / Slovakia approx. 6 %).*
- *The number of brake applications with a duration 30 s or more varies from 38 % (Italy) to 70 % (Sweden).*
- *The Swedish runs have by far the highest energy inputs of all runs: 6125 MJ/10.000 km in the reference wagon Sggmrs (empty).*
- *In transalpine runs in Switzerland and Austria energy inputs between 3581 and 3319 MJ/10.000 km were determined.*
- *Poland, Italy and Germany follow with values between 2067 and 2511 MJ/10.000 km.*
- *The lowest values were found in France, Belgium and the Netherlands with approx. 1254 MJ/10.000 km*

Translated quote from [2]

The already mentioned correlation between wear rate of brake blocks and brake energy in Section 5.4.2.1 is shown for the brake blocks CI and C952-1 in Figure 5.

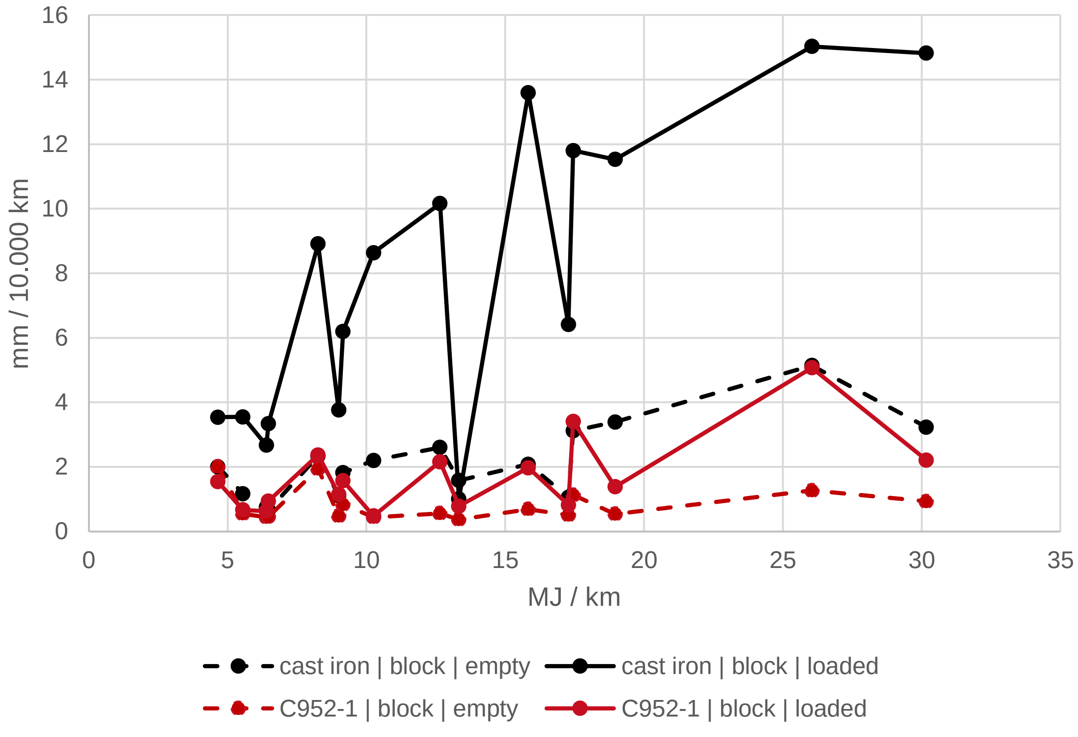

Figure 5: Influence of braking energy per distance on the <u>brake block</u> wear. Compiled with data from [2]

The different wear rates as a function of the loading state of the wagons and the respectively lower wear rates of the composite blocks are evident. In addition, an increase in the wear rates with increasing braking energy per distance can be seen in all cases.

A similar figure for the wear rates of the wheel is shown in Figure 6.

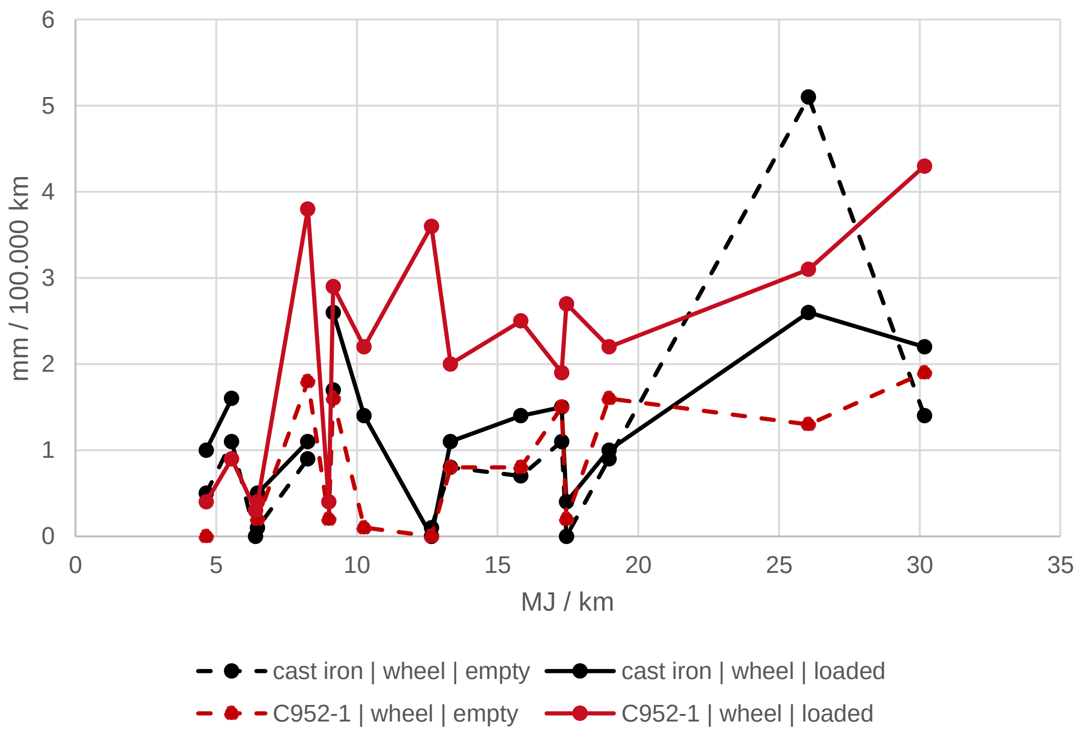

Figure 6: Influence of braking energy per distance on the wheel wear. Compiled with data from [2]

This again shows an increase in wear rates with increasing braking energy per distance. The wear rates of LL-braked wheels are higher especially when laden.

5.4.2.3 Wear of SS-Traffic Wagons in a Mixed Train

As mentioned in Section 5.4.1, the train of the “EuropeTrain” project should also contain some ss-traffic wagons. In the final report of the project, however, it becomes clear that no ss-traffic wagons were used but wagons marked with two stars **. The four wagons of the type Eanos (open wagon of standard design with four axles) have a maximum braked weight of 72 t in the laden state (90 t) which corresponds to a braked weight percentage of 80. Besides the fact that an ss-traffic wagons must have a maximum axle load of only 20 t, a braked weight percentage of 90 is necessary for ss-traffic conditions. The type description (Eano**s**) also indicates that the wagons are only made for s-traffic. However, the wagons were not fully laden during the runs so that they reached a total weight of 82 t. This corresponds to a braked weight percentage of 88. Overall, these wagons are likely to have been very similar to an ss-traffic wagon in their behavior. However, it is very likely that they were not equipped with kink valves. The final report contains conflicting information about this topic: *A limited number freight wagons for high speeds (SS or ** / ***) with kink valves [...] had to be incorporated* [translated quote from [2]], and *An SS-traffic freight wagon type with kink valve (acc. Usage guidelines for composite (LL) brake blocks) is used* [translated quote from [2]], and *They do not have kink valves, i.e. they take over the braking energy of the rest of the train* [translated quote from [2]]. However, it is unlikely that a non-ss-traffic freight wagon has a kink valve. Nevertheless, the “quasi” ss-traffic wagons of type Eanos should stand for “real” ss-traffic freight wagons in the following.

In addition to the four wagons of the Eanos type, four wagons of the Eas type (also open wagons of standard design with four axles) with a maximum braked weight of 52 t were incorporated in the train. These wagons have a braked weight percentage of 65 in the laden state (80 t), which corresponds exactly to the s-traffic conditions.

Table 8 shows the wheel wear rates of the two wagon types Eas and Eanos as a percentage to the average values of all types of wagons with the respective brake block type. It is noticeable that the wagon type Eas deviates relatively little from the average upwards in the empty state. A greater downward deviation is found for the CI-blocks and a smaller downward deviation for the C952-1 blocks, both in the laden state. In contrast, the wagons of the type Eanos differ upwards in all cases. In the case of CI-blocks in the empty state the deviation is 17,4 %, in all other cases it is over 30 %.

Table 8: Wheel wear rates of wagon types Eas and Eanos with different brake block types in % to the average values of all types of wagons with the respective block type. Own calculation using data from [2]

Wheel wear rate in % to the average of all wagon types with the same brake block type per **wagon type**	**Block type**			
	CI empty	CI laden	C952-1 empty	C952-1 laden
Eas	102,2	72,9	112,0	92,0
Eanos	117,4	141,1	185,9	132,9

As the wagon types Eanos and Eas are very similar aside from the brake design, it is obvious to compare the two wagon's wheel wear rates.

Table 9 shows the wheel wear rates of the wagon type Eanos in percent of those of wagon type Eas. In addition, the percentaged wheel wear rates are not only shown for runs with either empty or fully laden wagons, but also for runs where the wagons are loaded half of the distance respectively are empty in the other half.

Table 9: Wheel wear rates of wagon type Eanos in % of those of wagon type Eas. Own calculation using data from [2]

Wheel wear rate Eanos	**Block type**					
	CI empty	CI laden	CI 50 % empty, 50 % laden	C952-1 empty	C952-1 laden	C952-1 50 % empty, 50 % laden
in % Eas	114,8	193,6	**154,2**	165,9	144,4	**155,1**

It turns out that wear rates of the wagons of the type Eanos in the empty state and with CI-blocks are slightly higher than wear rates of the type Eas in the same configuration. However, in the laden state the wear rates are almost twice as high. In case of the C952-1 blocks there are less differences between laden and empty state. In both states, the wear rates of wagons of the type Eanos are about 1,5 times as high as those of the type Eas. In the scenario that the wagons are loaded one half of the distance and empty the other half, both blocks on the wagon type Eanos show almost identical wear rates of about 150 % of the respective wear rates of the type Eas.

It is thus that the "quasi" ss-traffic freight wagons of the type Eanos have a higher wheel wear than the s-traffic wagons of the Eas type regardless of the brake block type. There are differences between the two block types CI and C952-1 in dependency of the loading state of the wagon. However, if same portions of empty and laden state are assumed, the wear of a "quasi" ss-traffic wagon in a mixed train is about 1,5 times higher than the wear of an s-traffic wagon, independent of the two investigated brake block types CI and C952-1. It is to be noted, however, that the wagons were most likely not equipped with kink valves, which is a requirement for "real" ss-traffic wagons. This is also mentioned at one point of the final report: *They do not have kink valves, i.e. they take over the braking energy of the rest of the train* [translated quote from [2]]. The 1,5-fold wear rate correlates well with a 1,35-fold braked weight percentage (88 to 65). As a wagon with kink valves has probably less wear, this increase of the wear rate can be regarded as absolute limit.

5.5 Excel Tool "LCC-Modell Drehgestelle" (TIS LCC-Tool)

The Technische Innovationskreis Schienengüterverkehr (Technical Innovation Circle Rail Freight, TIS) is composed of representatives of the involved stakeholders in the rail freight sector such as car manufacturers, component manufacturers, wagon keepers, railway operators and shipping industry. These are in detail:

- AAE Ahaus-Alstätter Eisenbahn AG
- BASF SE
- DB Schenker Rail AG
- GATX Rail Germany GmbH
- Knorr-Bremse Systeme für Schienenfahrzeuge GmbH
- SBB Cargo AG
- VTG AG
- Waggonbau Graaf GmbH
- WBN Waggonbau Niesky GmbH

The aim of the TIS is to strengthen the innovation of rail freight and to increase the growth potential of the sector with innovative freight wagons by a common goal and approach of the stakeholders.

In this context, an Excel tool for the calculation of LCC of bogies was developed by members of the TIS in cooperation with hwh Gesellschaft für Transport- und Unternehmensberatung mbH. This shall serve the evaluation of innovative approaches.

The following information was obtained from the documentation of the tool [11]. The input data of the LCC tool was collected as part of a cross-sectoral study in TIS on the basis of real costs or sets of derived cost rates. The basis for the LCC calculations are average actual cost rates from the scheduled and unscheduled maintenance of bogies in rail freight. Where actual cost rates were not available, plausible estimates were carried out by the experts of the involved companies.

By now, only the running gear, including brakes, were considered for determining the LCC. Further developments of the model should consider other components of the wagon and also take into account the benefits of innovation through a capitalized value model.

The model in the current version uses the following methods and assumptions:

- The LCC are determined based on the discounted cash flow method. I.e. the costs occurring in the future are discounted at an interest rate of 8 %. This rate can be freely adjusted in the model. Also, inflation is taken into account, which is also adjustable and has a default value of 2,5 % annually.[9]

- The currency used in the calculation is the Euro.

- The LCC for bogies are calculated for a standard bogie Y25 1xBGU in the current model version. The LCC for the entire bogie are divided into the following four modules:

  - bogie frame,
  - wheelset,
  - brake system and
  - sensor technology

- The following four different versions for the braking system are considered:

  - axle-mounted disc brake,
  - conventional block brake (K-block) with two-sided braking,
  - conventional block brake (K-block) with one-sided braking,
  - conventional block brake (CI-block) with two-sided braking

- The used brake system has a significant impact on the LCC of bogies. Therefore, a braking configuration of the four above-mentioned brake systems can be chosen freely.

[9] The investigation of various interest rate scenarios by the authors led to implausible cost jumps. This was later confirmed by an employee of hwh Gesellschaft für Transport- und Unternehmensberatung mbH. The default values (8 % discounting and 2,5 % inflation) were therefore used for the calculations in this study.

- The LCC calculation includes the procurement costs, scheduled and unscheduled maintenance and residual values of the individual modules.

- The LCC model is designed for a time span of 20 years. Since the respective modules have a higher service life, a residual value for the respective modules is determined after expiry of 20 years.

- The values for the procurement costs represent a significant input for the LCC, as they have an influence from time t = 0. Thus also minor changes in the procurement costs have a significant impact. Furthermore, the costs for the same brake system may vary by up to 25 % depending on the wagon type and desired features. The procurement costs for the various braking systems in the model were presented by a brake system manufacturer. An agreement on average procurement costs per system / module was reached by the participants in the working group. The procurement costs, however, can also be set individually in the model.

- It is assumed for the calculation of LCC of bogies that they are incorporated into freight wagons, which are used in both unit train traffic and single wagon traffic (rate 50:50).

- Likewise, it is assumed for the calculation of LCC of bogies that they are used for both s-traffic and ss-traffic (rate 50:50).

The analysis of maintenance costs of the bogies partly showed significant differences between the various TIS companies. This is particularly due to the fact that the freight wagons of the TIS companies are partially used in different countries and there are various levels of maintenance costs. The cost rates used in the model therefore are average actual cost rates from European railway operations. Thus, the costs for the use of freight wagons in some specific European countries can vary (e.g. due to higher or lower workshop costs). The costs for the planned maintenance of bogies in the model can therefore also be adjusted individually.

The calculations carried out under this study were done for the axle-mounted disc brakes, the block brake with composite brake blocks with two-sided braking and for block brake with CI-blocks.

5.6 UIC Report "Railway Noise in Europe"

The UIC report "Railway Noise in Europe - A 2010 report on the state of the art" [8] covers, in accordance with its name, train noise, the political boundary conditions and possibilities for the reduction of railway noise. However, it also briefly addresses increased costs connected to the operation of wagons with K- and LL-blocks. Without more detailed information on boundary conditions or detection methods mentioned, the results of various studies from different experts are summarized in a table. This table also partly contains sources that have already been presented in the present report. In addition, three other sources are mentioned, which also should be mentioned here for completeness. The sources and the relevant results of this study results are shown in Table 10.

Table 10: Additional cost rates and sources from [8]

Source	Year	additional costs per wagon			
		for K-blocks		for LL-blocks	
		in EUR/km	in CHF/km	in EUR/km	in CHF/km
ERRI report	2004	0,007 - 0,025	0,007 - 0,026	-	-
PWC DG TREN assessment	2007	0,004	0,004	0,0041	0,0043
KWC DG TREN study	2009	0,0053	0,0055	0,0054	0,0056

6 Results

6.1 LCC when Using CI-blocks and Impact of Operational and Boundary Conditions on Wear

It has already been mentioned at several points in the presentation of the used sources in Section 5 that the operational and boundary conditions have a large influence on the wear behavior of brake blocks and wheels. For example, this is particularly evident in the projects “Whispering Train” and “EuropeTrain”.

The LCC of the running gear of the wagons are mainly determined by brake applications, namely the wear behavior the wear rates of brake blocks/brake pads and wheels/brake discs. The arising LCC when using CI-blocks are listed in this section in order to have a reference figure for comparison with the additional LCC of composite brake blocks and disc brakes listed in Section 6.2. In addition, the variations of wear rates and service lives of blocks and wheels when using CI-blocks and the monetary impact of these variations are shown exemplarily by means of the TIS LCC tool that was introduced in Section 5.5.

6.1.1 LCC when Using CI-Blocks

This section lists the arising LCC when using CI-blocks in order to have a reference figure for comparison with the additional LCC of composite brake blocks and disc brakes. For this purpose, the LCC per kilometer for a four-axle wagon with CI-blocks are shown as a function of the annual running distance. The values were calculated with the TIS tool with the default settings mentioned in Section 5.5[10]. Only LCC for running gear and brakes of the wagons are considered. The LCC for the bodies of the wagons are not considered due to the large spread among the different wagon types. The results are shown in Figure 7.

[10] The default values for inflation and discounting in particular seem rather high. Other values, however, led to incorrect results due to an error in the program. This has been mentioned in Section 5.5. However, employees of the TIS have confirmed the correctness of the calculations for the default values. Since the scope of this report are the differences between the different types of brakes and not the absolute costs after 20 years, the effects of different interest rates are less serious.

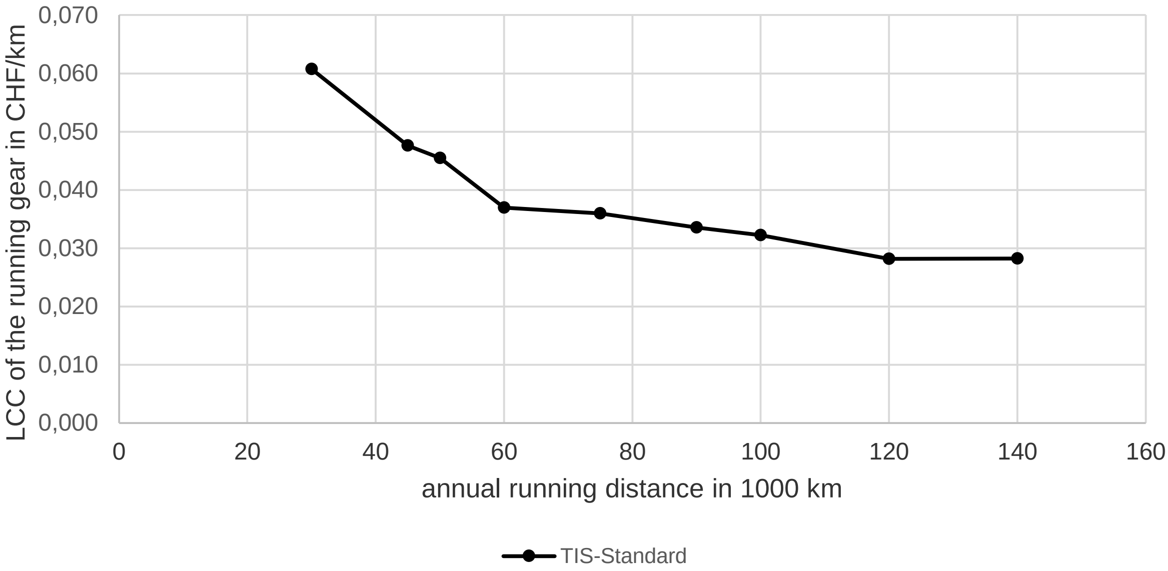

Figure 7: LCC of the running gear of a four-axle freight wagon with CI-blocks depending on the annual running distance for an observation period of 20 years. Compiled with data from [11]

A falling course of LCC per kilometer over the annual running distance can be seen. At an annual running distance of 30.000 km an amount of about 0,060 CHF per kilometer results. At an annual running distance of 140.000 kilometers, this figure halves to about 0,030 CHF per kilometer.

6.1.2 Different Wear Rates and Service Lives of CI-blocks and their Monetary Impact

The operational and boundary conditions have a major impact on the wear behavior of all types of brakes. Figure 8 shows the running distances to re-profiling of wheels when using CI-blocks specified in the TIS tool and the project “Dolomite Shuttle”. While the TIS tool uses a running distance of 250.000 km, a running distance of 350.000 km was determined in the project “Dolomite Shuttle”. This means a difference of 40 %. The wheel diameter wear rates of wagons with CI-blocks measured in the projects “Dolomite Shuttle” and “EuropeTrain” show a similar behavior. These results are shown in Figure 9. A 60 % larger diameter wear rate of the wheels with CI-blocks is found in the project “EuropeTrain” than in the project “Dolomite Shuttle”.

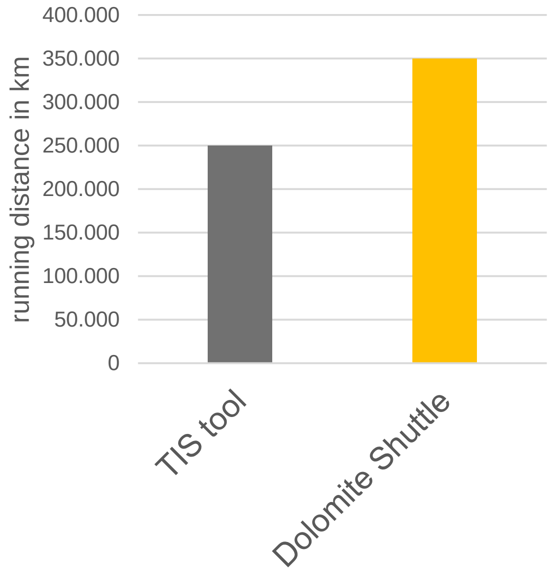

Figure 8: Running distance to re-profiling of wheels when using CI-blocks in km. Compiled with data from [11] and [4]

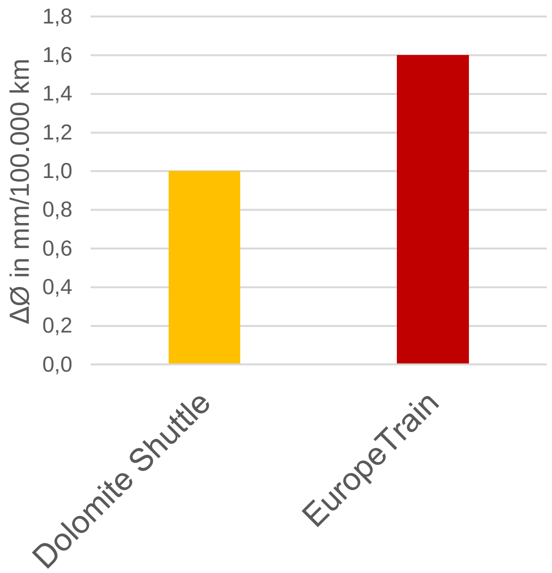

Figure 9: Wheel diameter wear rates when using CI-blocks in mm/100.000 km. Compiled with data from [4] and [2]

Figure 10 finally shows the service life of CI-blocks in km, as specified in the TIS tool and in the projects “Dolomite Shuttle” and “EuropeTrain”. While the values of the latter projects are very similar with 75.000 km respectively 78.000 kilometers, the TIS tool uses a service life of only 45.000 km. This value is 40 % smaller than in the project “EuropeTrain”.

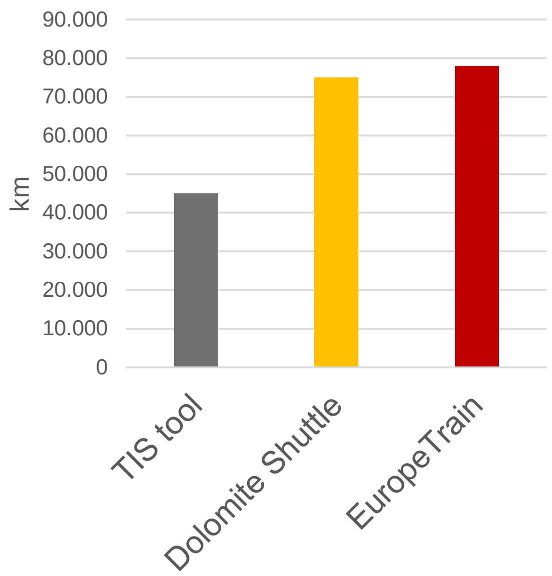

Figure 10: Service life CI-blocks in km. Compiled with data from [11], [4] and [2]

These results indicate that large differences in wear behavior also occur when using the conventional CI-bocks depending on the operational and boundary conditions. Consequently, this results in differences of the LCC. These differences of LCC, caused by the operational and boundary conditions have to be considered necessarily when evaluating the additional LCC of composite brake blocks and disc brakes in the following section.

Figure 11 shows an example of the monetary impact of the higher running distance of the wheels until re-profiling and the higher service life of the blocks of the project “Dolomite Shuttle” compared to the default values in the TIS tool in analogy to Figure 7. It can be seen that the LCC of the running gear with the values from the project “Dolomite shuttle” are lower for all annual running distances than the model with the default values of the TIS tool. The difference always results between 0,0020 and 0,0035 CHF/km. This corresponds to 5 % to 9 % of the LCC per kilometer of the TIS default case. This result is remarkable in light of the 40 % lower running distances before re-profiling and the 40 % lower service lives of the CI-blocks. It should however be noted, that all costs of the running gear, such as the procurement costs of the bogie frame and the costs for the regular maintenance works are considered.

Overall, it can be concluded that LCC vary also within a single brake type (in this case, cast iron block brakes) depending on the boundary conditions. This shows that the boundary conditions in the indication of (additional) LCC of composite brake blocks and disc brakes must be observed in each specific case. A specification of universally valid LCC which are independent of boundary conditions may at most be a rough guide.

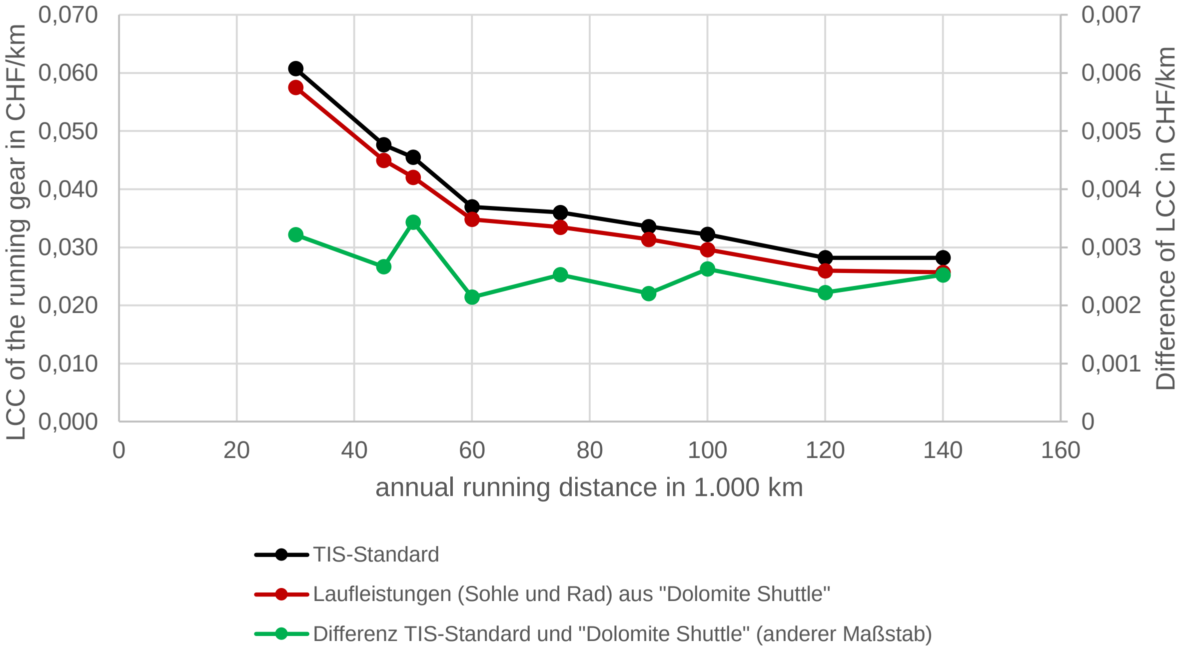

Figure 11: LCC of a the running gear of a four-axle freight wagon with CI-blocks depending on the annual running distance for an observation period of 20 years. Compiled with data from [11] and [4]

6.2 Additional LCC of Composite Blocks and Disc Brakes

Figure 12 shows the summary of all additional costs per kilometer of a four-axle wagon of the respective brake equipment compared to a wagon with CI-blocks presented in Section 5. Triangles stand for cost rates, which explicitly refer to a specific annual running distance. Squares also explicitly refer to a specific annual running distance and also consider an observation period of 20 years and interest rate effects. Solid lines with circles also consider an observation period of 20 years and interest rate effects and were determined using the LCC tool for different annual running distances. Dashed lines with circles or diamonds stand for values that do not have interest influences or specific observation periods and for which no specific annual running distance was specified.

The legends of each data set shows the project from which the data originates, and the respective boundary parameters of the data set.

A total of three different cost ranges are found in which the identified additional costs are located.

The highest cost range is located between about 0,032 CHF/km and 0,036 CHF/km. This range is negligible, because the two values represent improbable scenarios. The upper value (light blue triangle), that was determined with data from the project “Quiet Rhine”, considers the retrofitting costs for the K-blocks. However, in times of approved LL-blocks a retrofit of existing wagons to K-blocks is no longer to be expected. Only the installation of the K-blocks in new wagons is to be expected. In this case, the procurement costs of the brake system are only 350 EUR/366 CHF more expensive than those of the CI-braking system [11]. This difference does not remarkably affect the LCC of a wagon. Therefore, only the increased costs in operation, located in the second cost range (dark blue triangle) are to be considered. The second entry in the upper cost range is the LL-block C952 at a permissible equivalent conicity of 0,23 (yellow dotted line) in the project “Whispering Train”. As the recent allowable limit of the equivalent conicity is set to 0,40, this value is very restrictive. However, along with too less restrictive values with the permissible equivalent conicity of 0,60 in the lowest cost area (see below), this value results in a scatter band of the costs.

The middle cost range is located between about 0,017 CHF/km and 0,024 CHF/km. In particular the costs which have been determined within the project “Quiet Rhine” are located in this range. The costs for K-blocks compiled by the former railway research institute ERRI are also located in this range.

The lower cost range extends from just below 0 CHF/km to about 0,010 CHF/km. The costs calculated with the TIS LCC (both two-sided K-blocks as well as disc brakes) are located in this range. Furthermore, the costs determined in the studies of kwc and pwc and those identified in the project “Whispering Train” at a permissible equivalent conicity of 0,60 are located in this range.
It is worth noting that the disc brake is more economic than the two-sided K-block brake above an annual running distance of 55.000 km, based on calculations with the TIS LCC tool. With the only exception of the C952-block at a permissible equivalent conicity of 0,60, the disc brake is more economical than all investigated composite brake blocks

above 55.000 kilometers of annual running distances, according to the calculations. From 135.000 km of annual running distance, the disc brake is even more economical than the CI-block brake[11].

Figure 13 shows the additional costs of wagons with K-blocks only, in analogy to Figure 12. Figure 14 shows the additional costs of wagons with LL-blocks only, in analogy to Figure 12.

The three mentioned cost ranges can also be found in these two figures again.

[11] An annual running distance of 90.000 km is mentioned to be the limit value, from which the disc brake is more economical, when using the default settings of the LCC tool in the documentation of the TIS LCC tool [12]. However, the default settings of the LCC tool were also used in this study. It is not known why it comes to different results. Maybe the default values of the tool have changed since compilation of the documentation and publication of the tool.

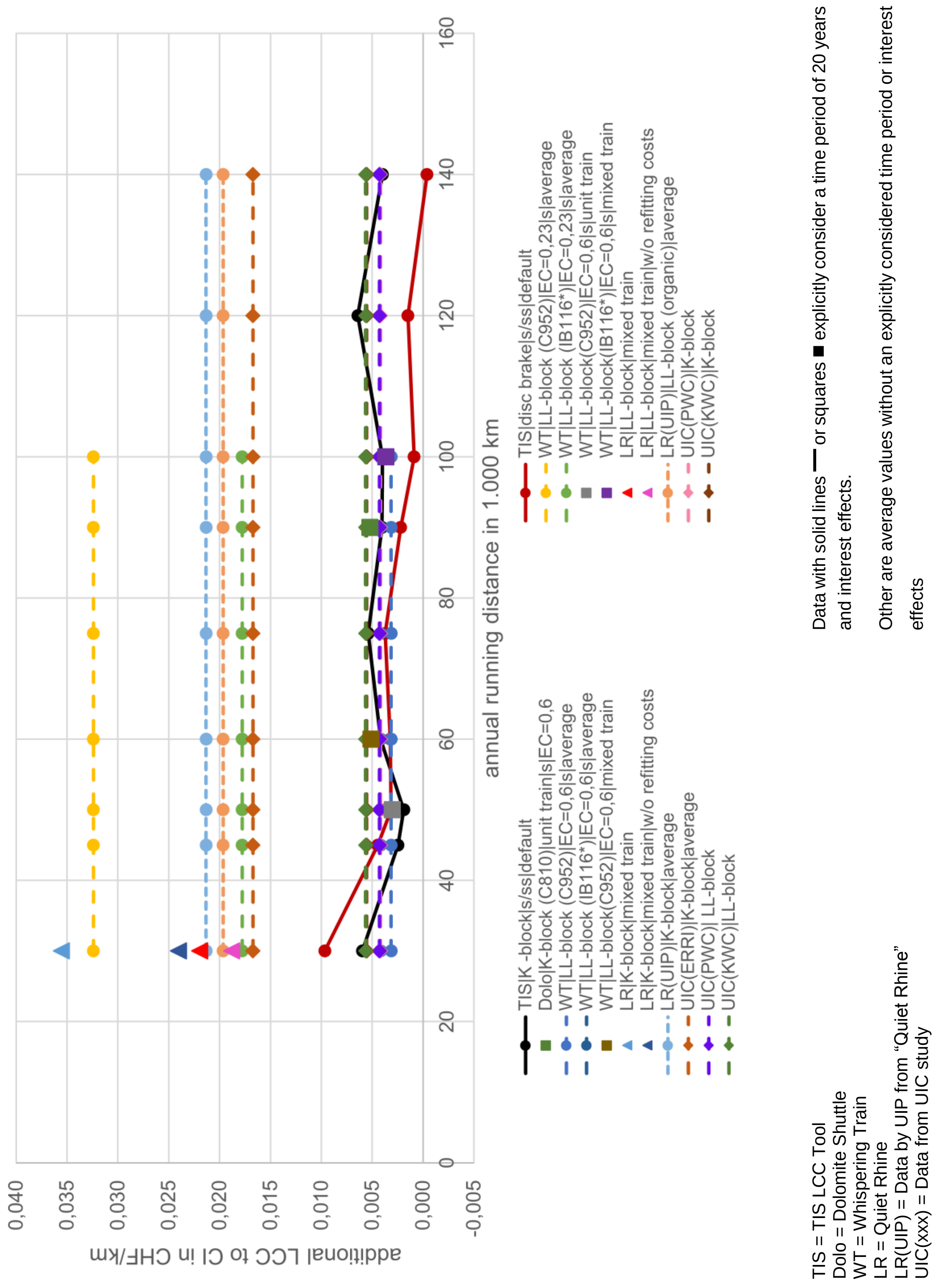

Figure 12: Additional LCC a of four-axle wagon with composite blocks / disc brake compared to a wagon with CI-blocks

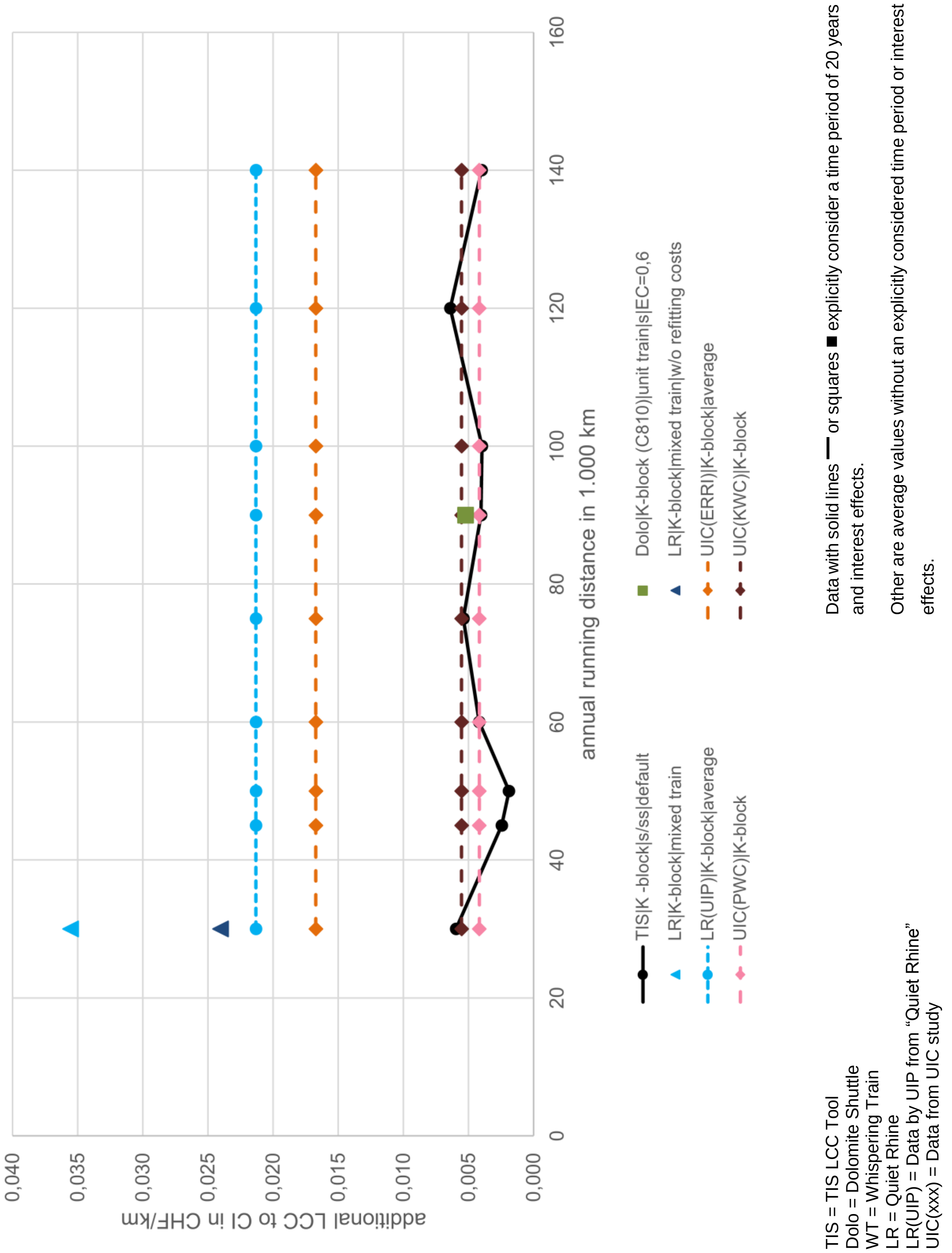

Figure 13: Additional LCC a of four-axle wagon with K-blocks compared to a wagon with CI-blocks

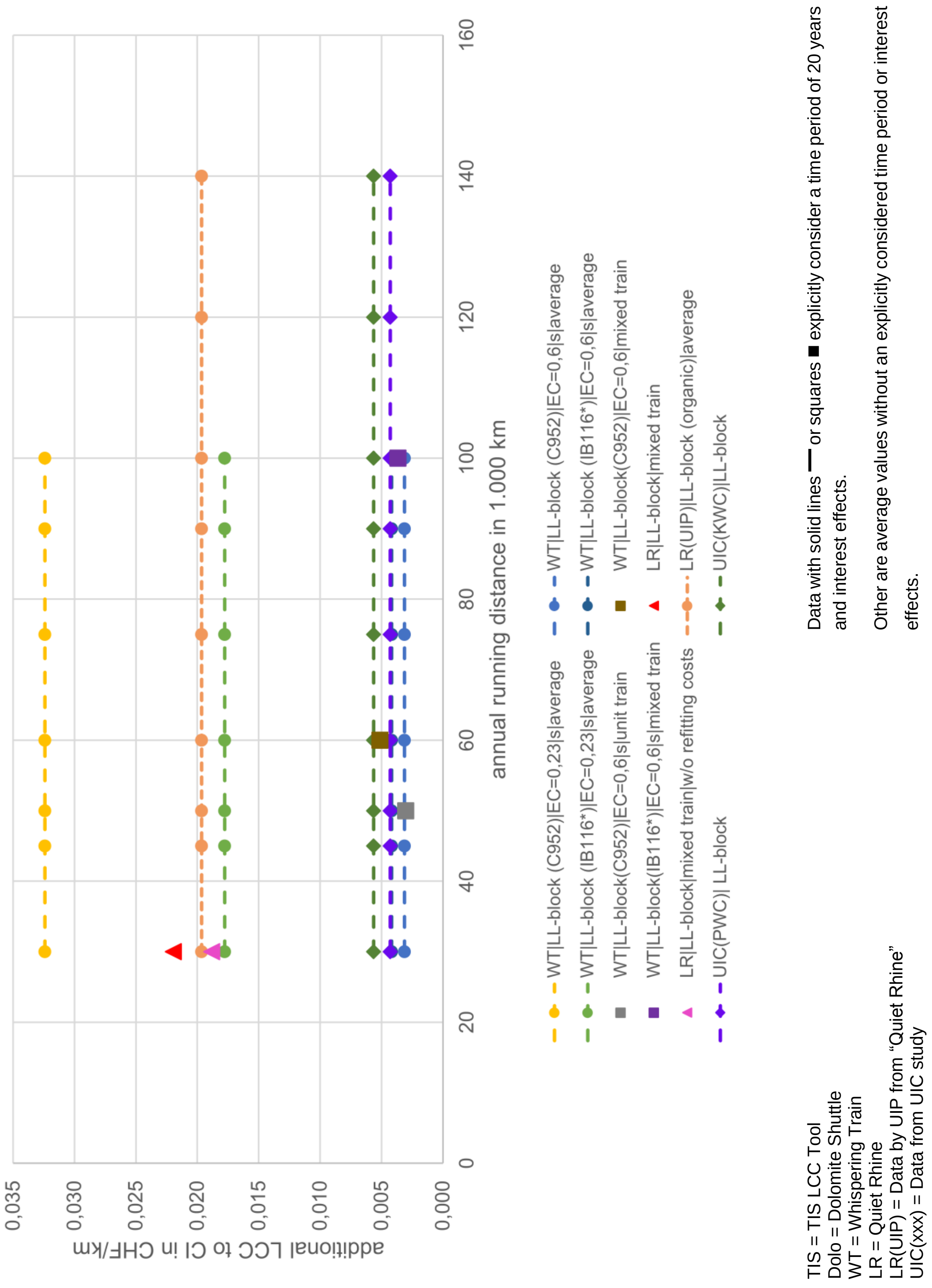

Figure 14: Additional LCC a of four-axle wagon with LL-blocks compared to a wagon with CI-blocks

6.3 Possible Measures to Reduce the LCC

As seen in the various sources in Section 5, the increased LCC when using composite brake blocks in particular result from the wear behavior of the wheels. Wheel wear hardly occurs when using the disc brake, which is why this brake system is advantageous with regard to the reduction of operating costs alone (see Figure 12). However, the relatively high procurement costs of the disc brake are a disadvantage. Thus the disc brake only becomes economical at high or very high annual running distances so far. Interest-free loans with a term of several years could be one way to mitigate this disadvantage, for example. Disc brakes could become more economical than CI-blocks at lower annual running distances in this case.

Basically, it can be noted for all braking systems that the reduction of pneumatic brake applications or the reduction of the amount of energy discharged with pneumatic brake applications lead to a significant reduction of the LCC of the brake system. The correlation of braking energy per distance and wear of the brake components is highlighted in Section 5.4.2.2. It also shows that there are significant differences from country to country regarding the frequency and the intensity of the pneumatic brake application.

The reduction of the frequency and the intensity of brake applications can be achieved through various measures:

- **Through the use of electrodynamic braking**. A part of the braking energy is virtually wear-free converted into electric power by the traction motors. Depending on the vehicle and the catenary system, the electric power can even be fed back again (regenerative brake). The existing **limits of permissible longitudinal compressive forces** of freight trains should be reviewed and adjusted to use this type of braking more often in the future. In addition, the use of **automatic couplers**, which allow significantly higher longitudinal compressive forces, should be checked. With these measures, it would be possible to increase the braking force applied by the locomotive and to reduce the force applied by the pneumatic brake. In case of service applications, it might be possible to entirely forego pneumatic brake applications.

- **Through the widespread introduction of ETCS Level 2**. By increasing the (electronic) signal visibility range, the driver can reduce speed at restrictive signal aspects by rolling and electrodynamic braking at an early stage.

- **Through intelligent real-time scheduling systems** such as “Adaptive Lenkung” (ADL) in Switzerland. Through these systems, the entire traffic flow is optimized and the number of avoidable stops is reduced. With this system a train would, for example, lightly reduce speed at an early stage in order to pass a signal without stopping later.

Not only do the aforementioned measures reduce the brake-related LCC of wagons, they also help saving a noteworthy amount of energy and therefore a noteworthy amount of money.

Berlin, 9th of September 2015

M. Hecht

Prof. Dr.-Ing. Markus Hecht

D. Jobst

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